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DOE/NASA/0058-79/3
NASA CR-159497

EXECUTIVE SUMMARY

MOD-1 WIND TURBINE GENERATOR ANALYSIS AND DESIGN REPORT

General Electric Company
Space Division

May 1979

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract NAS 3-20058

for
U.S. DEPARTMENT OF ENERGY
Office of Energy Technology
Division of Distributed Solar Technology

NOTICE

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Advanced Energy Systems
Philadelphia, Pennsylvania 19101

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Washington, D. C. 20545
Under Interagency Agreement EX-77-A-29-1010

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Background

The extraction of power from the wind is not a new concept, especially in the application of mechanical power to pump water or to mill grains. However, the generation of electrical power from the wind dates only from the turn of the century. Wind turbine generators achieved a measure of technical and economic practicality in rural and remote areas of the country during the 1920's, but the gradual extension of electrical utility networks and the availability of low cost fossil fuels led to their abandonment by the 1940's.

The early wind turbine generators were generally limited to power levels below 10 kilowatts and were operated independently of an electric utility network. The Smith-Putnam machine of the 1940's was the singular attempt in this country to develop a large-scale unit with the capability of being connected to an electric utility network. Interest in wind power waned until the 1970's when shortages in energy and the increasing costs of fossil fuels forced the nation to reassess all forms of available energy. A national wind energy program was established to develop the technology necessary to enable wind energy system to be cost competitive with conventional power generation systems and to be capable of rapid commercial expansion for producing significant quantities of electrical power. As part of that program, General Electric's Space Division was contracted to design and build, under the direction of NASA - Lewis Research Center and sponsored by the Department of Energy, a wind turbine generator having a nominal rating of 1.8 megawatts, designated Mod 1.

History of the Mod 1 Program

The Mod 1 program is being conducted in six phases: Analysis and Preliminary Design (culminating in a Preliminary Design Review), Detail Design (ending with a Final Design Review), Fabrication and Assembly, System Testing, Site Preparation, and Installation and Checkout. Major milestone dates for these phases are shown in Table 1-1. This report is intended to describe only the results of the first two phases; that is, activities leading to the completion of Detail Design. Although this report places emphasis on a description of the design as it finally evolved, it is of some interest to trace the steps through which the design progressed in order to understand the major design decisions.

The design requirements specified by NASA for the Mod 1 wind turbine generator in the contract Statement of Work reflected the conclusions of two previous design studies by contractors, as well as the experience of NASA-LeRC in designing, building, and operating the Mod 0 unit. These specifications, summarized in Table 1-2, were utilized as the design starting point. Therefore, during the Analysis and Preliminary Design phase, only certain parameters were optimized and certain design options were investigated. A major decision was the selection of a rigid rotor hub as opposed to a teetered hub. A trade-off study was conducted in which the effects on rotor hub, supporting structure, and tower as a result of load reduction from teetering were weighed against the increased complexity and programmatic risks of a teetered hub design. Supporting this study, detailed layouts were prepared of rigid hub and teetering hub

concepts, with corresponding load analyses for selected critical wind and gust conditions. In the process of conducting this study, it was discovered that the pitch control mechanism, because of its required location and its role in determining blade torsional stability, had to be much more robust than had been anticipated and greatly influenced the size, weight, and cost of all adjoining mechanical components. As a result, an in-depth design study was initiated to evaluate various mechanism concepts, resulting in selection of the system that will be described later. Undoubtedly, the size and complexity of the pitch control mechanism was the deciding factor that made it difficult to incorporate a teetering feature and so tipped the scales in favor of a rigid hub design.

A major analytical task of the first program phase was the verification of analytical computer codes used for dynamic simulation and load analyses. The results of this and other analytical tasks, as well as the conclusions of the teetered hub study, were orally presented to NASA at a First Phase Formal Review, just prior to the Preliminary Design Review (PDR).

At PDR, the results of the Analysis and Preliminary Design tasks were presented as follows:

a. Design features were described.
b. Analyses, completed and planned, were discussed.
c. Any design deficiencies established by analysis were identified.
d. Failure modes were reviewed.
e. Material selections were justified.
f. Fabrication procedures were discussed.
g. Inspection and testing techniques and criteria were discussed.
h. Approval to deviate from specifications was obtained, where required.
i. Approval for procurement of long-lead items was obtained.

Approval of the Preliminary Design permitted the next phase, Final Design, to proceed.

During Preliminary Design and through the initial stages of Final Design, responsibility for the blade, rotor hub, and pitch control mechanism was subcontracted to Hamilton-Standard in Windsor Locks, Conn., along with related analytical tasks. Hamilton-Standard proposed a filament wound, glass fiber reinforced plastic blade with fabrication in turn subcontracted to Allegheny Ballistics Laboratory. When it became evident that the filament wound blade design was having problems, a back-up design study for a metal blade was initiated with Lockheed Aircraft Corp. Subsequently, Hamilton-Standard's participation was terminated and the design and fabrication of a metal blade was subcontracted to Boeing Engineering Company.

At this stage in the program with the delay caused by introduction of a new blade concept, the opportunity was taken to reassess the design requirements while the final design was still not yet frozen. Among the requirements re-examined at this time were rated power, rated wind speed, blade ground clearance, design gust conditions, blade profile, downwind rotor placement, and ambient temperature extremes. As a result, recommendations to change certain of the requirements were made to NASA and the negotiated changes are reflected in Table 1-2. A review of the total program costs at this time also resulted in cancellation of the option to fabricate a second unit.

While a new metal blade design was initiated, final design of the remainder of the wind turbine generator system was completed and a Final Design Review was held. However, final drawing releases of some components whose design depended on the blade were delayed until the required information was available. The blade design progressed

through PDR and FDR, similar to the steps taken for the remainder of the system.

Table 1-1

Mod 1 Program Milestones

Program Go-Ahead	July, 1976
First Phase Formal Review	December, 1976
Preliminary Design Review (less blade)	January, 1977
Reassessment of Design Requirements	June, 1977
Final Design Review	August, 1977
Metal Blade Go-Ahead	September, 1977
Blade Preliminary Design Review	December, 1977
Blade Final Design Review	March, 1978
Assembly Start	May, 1978
Site Preparations Start	June, 1978
System Test Start	August, 1978
Shipment to Site (less blade)	September, 1978
Sub-system Checkout	March, 1979
Blade Shipment to Site	April, 1979
System Checkout	May, 1979

Two tasks that supplemented the Detail Design tasks were the Safety Review and the Failure Modes and Effects Analysis (FMEA). The Safety Review was imposed as an internal General Electric-Space Division requirement, a prerequisite to approval of the final design. This review was conducted by qualified specialists within the Space Division who were not associated with the Mod 1 Program.

Table 1-2

Summary of Design Parameters

Rated Power	2000 kWe @ 11.4 m sec^{-1} (25.5 mph) 1800 kWe @ 11.0 m sec^{-1} (24.6 mph)
Cut-In Wind Speed	5 m sec^{-1} (11 mph) max.
Cut-Out Wind Speed	15.9 m sec^{-1} (35 mph)
Maximum Design Wind Speed	67 m sec^{-1} (150 mph at shaft center line - assume no wind shear)
Rotors per Tower	1
Location of Rotor	Downwind of Tower
Direction of Rotation	CC (looking upwind)
Blades per Rotor	2
Cone Angle	9^{o}
Inclination of Axis Rotation	None
Rotor Speed Control	Variable Blade Pitch
Rotor Speed	34.7 RPM
Blade Diameter	61 meters nom. (200 ft. nom.)
Airfoil	44XX series
Blade Twist	11^{o} Linear
Tower	Steel Truss
Blade Tip to Ground Clearance	12 meters (40 ft.)
Hub	Rigid
Transmission	Fixed Ratio Gear
Generator	60 Hz/Synchronous
Yaw Rate	$.25^{o}$/sec
Control System	Electro Mechanical/Microprocessor
System Life :	
Dynamic Components	30 years (with maintenance)
Static Components	30 years (with maintenance)

NOTE :

1. All wind velocities measured at 9 meters (30 ft.) elevation.

Failure Modes and Effects Analysis

The FMEA was directed primarily at identifying those critical failure modes that would be hazardous to life or would result in major damage to the system. As a result, the analysis was conducted from the "top down", minimizing the extent of analysis that would lead to trivial conclusions, had the analysis been approached from the "bottom up". For example, a component-by-component analysis of the lubrication system was not pursued, once it had been established that all single lubrication system failures lead to the same, non-critical conclusion.

The criteria used for evaluation during the FMEA is that none of the following injuries or damage shall occur because of a single failure or a single failure following an undetected failure of the wind turbine system.

Category I: Failures which would result in death or serious injury to the operator or general public.

Category II: Failures which would result in major or significant damage to the wind turbine system, extended outage, or damage to the connected utility.

The FMEA worksheets went through several stages of review, including review by qualified GE specialists outside of the Mod 1 program and two reviews by knowledgeable NASA LeRC personnel. Corrective action was taken whenever recommended.

Maintainability

This topic was addressed on a continuing basis during the design phase, and provisions were built-in for ease of maintenance. Whenever possible, standardized off the shelf components were chosen for minimum maintenance, with the normal maintenance cycle initially set at 6 months.

SECTION 2

SYSTEM DESCRIPTION

SECTION 2

SYSTEM DESCRIPTION

2.1 GENERAL CONFIGURATION

The general configuration of the Mod 1 wind turbine generator is shown in Figure 2-1. The two-bladed rotor is approximately 200 feet (61 m) in diameter and is located downwind of the tower 140 feet (46 m) above the ground. The nacelle, enclosing all equipment mounted on top of the tower, is driven to rotate about the vertical axis of the tower in response to changes in the wind direction. The truss tower is made up of tubular and channel structural shapes with bolted joints. It is 12 feet (4 m) square at the top and 48 feet (16 m) square at the bottom, and is anchored to reinforced concrete footings at each leg. At ground level is located an environmentally controlled enclosure for sensitive control and power generation equipment as well as elements of the data system. Within the fenced area are also located the back-up battery system, the step-up transfomer connecting to the utility, and the lift device that provides access to the top of the tower.

The total weight of all equipment above ground level is approximately 650,000 pounds (290,000 kg) of which 310,000 pounds (140,000 kg) is the weight of the tower. In order to facilitate transportation and erection, the system is designed to permit shipment in a number of subassemblies not exceeding 100,000 pounds (45,000 kg) each. The approach requires more high elevation assembly, but eliminates the need for a costly, high capacity crane at the site.

Equipment mounted on top of the tower is shown in more detail in Figure 2-2. Major components identified below are also discussed in more detail in subsequent sections of this report.

2.2 ROTOR

The steel blades are attached to the hub through a three-row roller bearing that permits the pitch angle of each blade to be varied 105 degrees from feather to full power. Blade pitch is controlled by hydraulic actuators operating through a mechanical linkage with sufficient capacity to feather the blades at a rate of 14 degrees per second. The rotor is supported by a single bearing with two rows of tapered rollers.

2.3 DRIVE TRAIN

Torque from the rotor is carried by a floating shaft to a speed increaser gearbox. The gearbox increases the speed through three stages to match the 1800 rpm synchronous generator, also connected to the gearbox through a floating shaft with flexible gear couplings. The high speed shaft incorporates a dry disk slip clutch protecting against torque overloads, and a disk brake that stops the rotor and holds it in a parked position. The gearbox lubrication system also provides oil to the rotor bearing and dissipates waste heat by means of a passive cooler suspended below the nacelle.

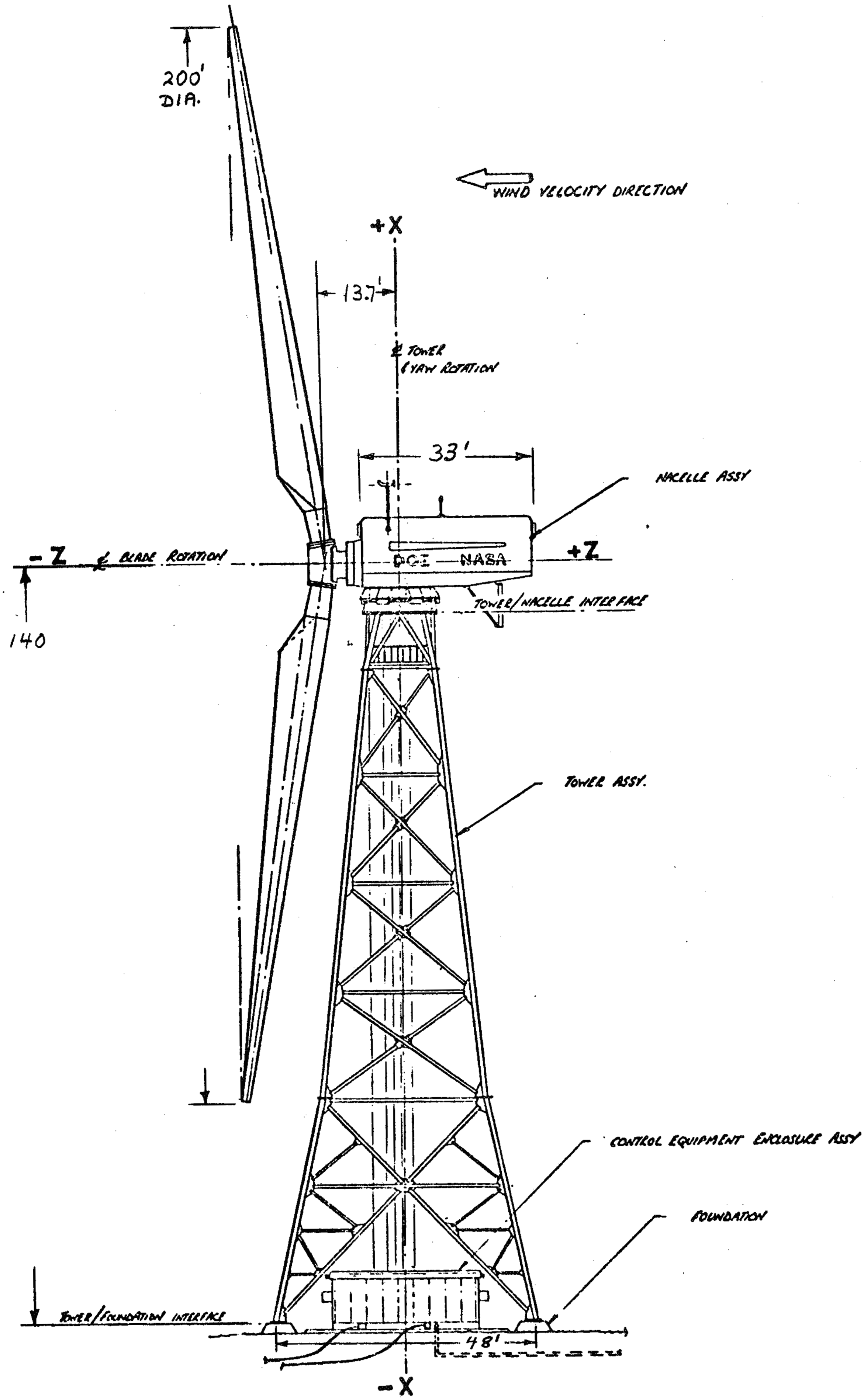

Figure 2-1 Mod 1 WTG General Configuration

The low speed shaft and the gearbox first stage shaft are hollow to permit passage of electrical cables from the rotor to a slip ring assembly.

2.4 POWER GENERATION EQUIPMENT

A synchronous ac generator is driven at 1800 rpm by the high speed shaft. A shaft-mounted, brushless exciter, controlled by a solid-state regulator and power stabilizer, provides voltage control. Generator output at 4160 volts is brought by cables and a slip ring at the yaw bearing down the tower to the ground enclosure. Surge capaciters and related power generation equipment are mounted in a caged enclosure below the generator.

2.5 NACELLE STRUCTURE

The welded steel bedplate is the primary nacelle structure, supporting all equipment mounted on top of the tower and providing a load path between the rotor and the yaw structure. Equipment mounted on the bedplate includes the pitch control and yaw drive hydraulic packages, the control and data system units, access ladders and walkways, oil coolers, lubrication pumps, hydraulic plumbing, and cables for electrical power and instrumentation. A removable fairing encloses the nacelle, incorporating inlet and outlet louvers for cooling air. The fairing also provides mounting for wind sensors, obstruction lights, and interior lighting.

2.6 YAW DRIVE

Rotation of the nacelle about a vertical axis is provided by the yaw drive system, consisting of upper and lower structures, a cross-roller bearing, dual hydraulic drive motors, and six hydraulic brakes. Each yaw motor drives a pinion meshing with a gear on the inner race of the yaw bearing. The yaw brakes control dynamic excitations in yaw by maintaining a rigid connection, and assist in damping yaw motions while the nacelle is being driven. Power and signal data are transferred to the tower-mounted cables by slip-rings.

2.7 SYSTEM WEIGHT

A summary of system weight is given in Table 2-1.

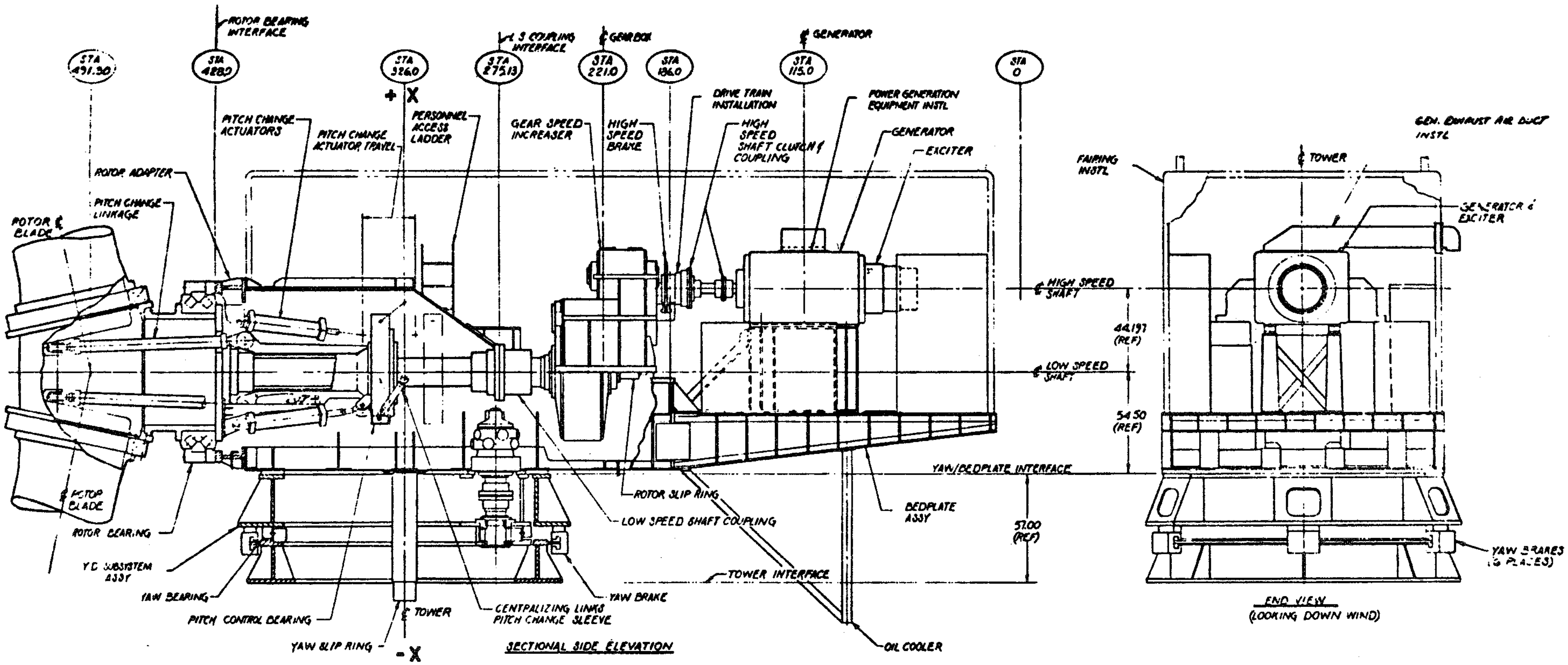

Figure 2-2. Nacelle Installation

TABLE 2-1

SYSTEM WEIGHT BREAKDOWN

ROTOR ASSEMBLY		103,000 lb
Hub	15,000	
Blades	36,000	
Bearings, supports	29,000	
Pitch Control Mechanism	11,000	
Pitch Control Hydraulics	12,000	
NACELLE ASSEMBLY		171,000 lb
Bedplate	68,000	
Fairing	5,000	
Generator	14,000	
Power Generation Equipment	1,000	
Shafts and Couplings	18,000	
Gearbox	58,000	
Lube, Hydraulic System	4,000	
Control and Instrumentation	1,000	
Cables, Lights, etc	2,000	
YAW ASSEMBLY		56,000 lb
Yaw Structure	34,000	
Bearing	13,000	
Yaw Brake	1,000	
Yaw Frive	8,000	
TOWER ASSEMBLY		320,000 lb
Structure	313,000	
Lift Device	1,000	
Cable, Conduit	6,000	
TOTAL (Excluding Ground Equipment)		650,000 lb
GROUND EQUIPMENT (Including Transformer)		54,000 lb
TOTAL		704,000 lb

SECTION 3

STRUCTURAL DYNAMICS

SECTION 3

STRUCTURAL DYNAMICS

3.1 OBJECTIVE

The objective of the structural dynamic analysis is to assure adequacy of the system design for the range of operating conditions experienced in service. Factors which influence the system dynamic design are:

1. Proper placement of system resonant frequencies
2. Accurate prediction of operational loads and deflections
3. Selection of a design approach which minimizes sensitivity to dynamic loading

Because of the many dynamic interactions within the WTG system, proper placement of the system resonant frequencies can not be directly related to the subassembly dynamic characteristics alone. Similarly, design loads may be amplified by the structural response to cyclic excitation. The design approach can provide parameters which are variable and difficult to predict, and can increase dynamic loading. By analyzing system dynamic characteristics for specified subassembly characteristics considering the variability of key parameters, dynamic adequacy of the system can be evaluated early in the design phase and modifications made to assure adequacy of the final design.

Frequency placement and operational design load requirements are defined in the NASA Statement of Work. The frequency requirements are an outgrowth of the original NASA specification and frequency placement sensitivity studies, discussed in Paragraph 3.3. Because of the high number of cycles accumulated over 30 years at the high wind speeds, the cyclic loads at the cutout speed (35 mph) are used to design the system for infinite life. The steady state vibratory loads calculated at this speed are multiplied by dispersion factors to account for gusts and wind directional changes.

3.2 SYSTEM SYNTHESIS

3.2.1 ANALYTICAL APPROACH

Analysis of the WTG system was accomplished by separation of the system into major substructural segments. This system naturally divided at: bearing attachments located at each rotor blade, at the hub, low and high-speed drive shaft supports, and the bedplate/tower interface. A natural division was also made at the the blade pitch actuator attachment and the yaw drive/brake mechanism. This division resulted in five major substructures: tower, bedplate, hub/shaft and two rotor blades.

Each major substructure was then analyzed separately, using finite element models to obtain substructure vibration mode shapes and frequencies with free attachment coordinates. Then, the stiffness coupling method of modal synthesis was used to assemble the complete structure through stiffness links (stiffness matrices) representing the bearings and drive mechanisms. This assembly of

component modes and frequencies through flexible links was then used to derive eigenvalues and corresponding eigenvectors representing the system dynamic model.

The flow of the dynamic model assembly is shown in the block diagram of Figure 3-1. This diagram shows the subsequent input of modal parameters into response and dynamic loads analysis programs. Revisions to the dynamic model were made after frequency placement checks and preliminary stress analysis, where necessary, to meet design criteria. Results of the dynamic loads analysis were then used to check loads used in the final stress analysis.

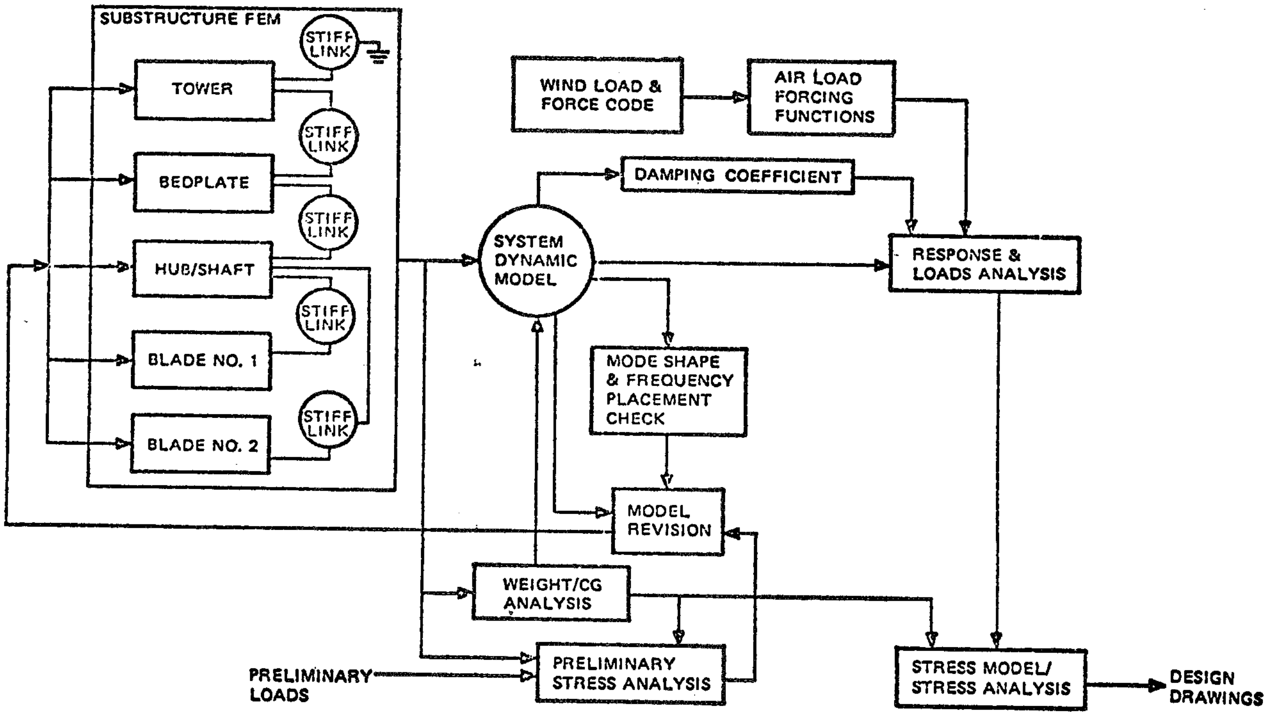

Figure 3-3. Mod-1 Analysis Flow

3.2.2 CODE VERIFICATION

A key element in the program was the development and verification of the GETSS (GE Turbine System Synthesis) computer code. Data provided by the GETSS code was verified by comparing analytical predictions with measured results for the Mod-0 WTG under various operating conditions. Development of the Mod-0 dynamic model followed the same methods used in the Mod-1 analysis.

The final solution resulted in 20 modes under 10 Hz. These modes were used to compare directly with results reported in NASA TMX-71879, 3426, and the final report by the University of Cincinnati on modal testing. This comparison showed agreement in modal frequency within less than 1 percent for the first tower bending (N-S), first tower torsion and second tower bending (N-S). The first rotor flatwise and edgewise modes differed by only 3 to 4 percent and others by not greater than 9 percent. A check of modal displacements also showed good agreement for tower bending modes (Modes 4 and 5). The upper bay motion showed similar diagonal motion to that measured on the test, along with a similar amount of displacement.

3.3 SENSITIVITY ANALYSIS AND FREQUENCY PLACEMENT

Coupling between the various WTG substructures is significant and makes the influence of component structural changes on the system dynamic response a complex problem for analysis. Structural coupling exists between the rotor, shaft, bedplate, and tower such that as rotor position changes, the dynamic characteristics of the system change. An understanding of the system sensitivity to these interactions was aided considerably by the modal synthesis approach which was used in the evaluation of the modal contributions to the dynamic loads. Parameters investigated included blade/tower frequency placement and bearing stiffness variations at major interfaces. The results of this study are summarized and briefly discussed as follows:

1. Yaw Drive Torsional Stiffness. Large increases in blade flapwise moment are evident for decreases in yaw drive stiffness below the design value. Less dramatic increases in load occur at the yaw bearing and tower root. With yaw brake engaged the actual stiffness of the yaw drive system is adequate.

2. Tower/Blade Tuning. There is a significant increase in loads when unfavorable coupling occurs between tower bending and blade flapping modes. It was concluded that with a blade flap frequency in the range of 2.15 to 2.7P, unfavorable coupling could be avoided by ensuring that the tower bending frequency exceeded 2.8P. As a result, a change was made in the design requirements specified by NASA to raise the tower bending frequency placement from 2.2P to 2.8P.

3. Blade Retention Bearing Stiffness. Shear and axial stiffness variations were found to have negligible effect on system loads, while a reduction in bending stiffness by a factor of 24 produced a decrease in most cyclic loads. The only significant increase was a 12% growth in tower base cyclic yaw moment.

4. Main Rotor Bearing Stiffness. All loads were relatively insensitive to changes in radial and axial stiffnesses; reductions by a factor of 100 were necessary to produce any noticable change. A decrease in bending stiffness from the design value of 2.25×10^{10} to 4.0×10^{9} in-lb/radian did not significantly affect the majority of the loads. The largest change was a 65% increase in tower base cyclic bending moment.

5. Foundation Stiffness. A parametric study was performed to evaluate the effects of soil or foundation stiffness. Tower natural frequencies were computed for a range of foundation stiffnesses that varied from approximately one-half to twice the anticipated values, laterally as well as vertically. The results showed tower frequencies for the first ten modes varied less than 5% from the expected value.

3.4 BLADE LOADS

Analysis of measured data from MOD-0 revealed significant scatter of the blade cyclic load amplitudes, and was observed to occur at any given wind speed. Evaluation showed that the mean of the scatter band was governed by the tower shadow, wind shear and gravity (which are always present) while dispersion from the mean was attributed to atmospheric turbulence (gusts).

To assure the regularity of the dispersion of the cyclic moments from its mean, a probability plot was constructed from the MOD-0 cyclic flap bending histograms. It was observed that the General Electric GETSS program predicted the mean of the scatter for MOD-0 data. Since standard practice for design to random loading is to base stress calculations on the 99.8 percentile loads (3σ), those loads predicted by GETSS (which are at the 50th percentile) were multiplied by a factor to produce the maximum of the load dispersion observed on the MOD-0 data. For the MOD-1 design, the dispersion factor was found to be 1.9 for the flap bending cyclic loads. Chord bending data similarly indicated a factor of 1.5. Since these factors are relatively insensitive to wind speed the same factors were used in all of the blade load cases.

3.5 STRUCTURAL LOADS

It is clear that loads at other points in the structure would have different dispersion factors. Unfortunately, only blade data were analyzed on Mod-0 so a means had to be developed to approximate the dispersion factors at other interfaces of the Mod-1 structure. The approach taken was to define (and then analyze) a "design gust condition" that satisfied the following criteria.

1. Consistent with Mod-0 data - predicts "3σ" blade loads
2. Consistent with wind data supplied by Professor Dutton, Reference 1.
3. Compatible with existing analytical capabilities

These conditions were met by the change in steady-state loads that occur in going from 25 to 35 (or 35 to 25) mph with an inflow angle from -32° to $+32^{\circ}$. This corresponds to a fully immersed, fully compensated gust of 10 mph. The two wind speeds, 25 and 35 mph, correspond to the rated and cut-out velocities of the Mod-1, so that the design condition represents real operating conditions.

Calculation of the dispersed load factor was then determined by the range of the load between these two steady-state cases. The dispersion factors calculated by this procedure were applied to the loads predicted by GETSS at 35 mph to generate fatigue loads. Most of the dispersion factors thus obtained were below 2.0; however, a minimum dispersion factor of 1.5 was set regardless of the factor that was calculated.

[1] Dutton, J.A., Private Communication to S.L. Macklis, May 16, 1977.

SECTION 4

STABILITY ANALYSIS

SECTION 4

STABILITY ANALYSIS

This section describes the model and analyses utilized in assessing analog control system performance and stability. Both frequency and time domain regimes were examined. The power transfer path was examined from the wind to the rotor, through the drive train shafts and gearbox to the generator and the utility grid.

4.1 REQUIREMENTS

4.1.1 STATEMENT OF WORK

The NASA Statement of Work requires that a control analysis be performed using models representing ties to both large and small utility networks. The SOW defines the gust models to be used and pitch change rates, as well as general requirements for safe starting and synchronization, electrical stability, and torque variation.

Two important requirements, voltage dip response and connection impedance range, are derived from electric utility standards and practices at the distribution voltage level characteristic of Mod-1.

Voltage deviation is objectionable to the consumer for reasons such as incandescent lamp flicker and television picture changes. The derived Mod-1 requirement of ± 5 percent for infrequent occurrences down to ± 1.5 percent at tower shadow frequency is below typical utility limits. This voltage performance is measured at a critical customer location, not at the generator terminals.

Electrical systems tied to a utility grid with generation are typically represented as having an impedance (resistance and inductive reactance) connection to a constant-voltage, constant-frequency source or infinite bus. Large-scale system analyses take one generator as reference and permit all voltages to vary in magnitude and relative phase to the reference. In comparison with fossil or nuclear-powered generators in the hundreds of megawatts or gas turbine-powered units from 20-60 megawatts, the 2 megawatt Mod-1 generator connecting to a radial feeder can be considered analytically as just the generator system, a connection impedance, and the reference infinite bus. Loss of detail due to condensing the network to an impedance is very small.

As the dynamic stiffness of the generator air gap is a function of real and reactive power level and connection impedance, a broad range of conditions is required to assess stability. The system range in size, without specific data on a site and nearby generation, is accommodated by the range of connection impedance. At the site on Howard's Knob near Boone, NC, the effective impedance is at the lower, more stable, end of the examined range.

4.1.2 WIND CHARACTERIZATION

The torque produced by the wind rotor and the structural response of the entire wind turbine is strongly influenced by the variability of the wind.

Three-time domain forms of wind forcing function amplitude-histories were used during the course of design and analysis:

1. 1-Cosine Model - from the original SOW.
2. Probabilistic Time History - from the current SOW.
3. Random Noise - based on probabilistic data

Model No. 1 while based on extensive wind records, has a smoothed amplitude-time characteristic that does not represent actual wind disturbances as well as Model No. 2, also based on a large amount of actual wind data. Ranking of severity and probability of occurrence is based on amplitude and rate of change of amplitude. Model No. 3 is used for runs of several minute duration using random noise filtered to provide a power spectral density consistent with the data from which Model No. 2 is extracted.

4.1.3 OBJECTIVES

The primary objective of the analysis is to assess stability, where stability is defined in three ways :

1. Classic Stability Frequency domain based criteria of no positive real eigenvalues for the system as a small signal linerarized around a variety of operating points.

2. Dynamic Stability Time domain-based criteria of maintaining synchronism and acceptable voltage performance on the non-linear system simulation for large gusts or electrical faults.

3. Deviational Stability Time domain-based criteria of minimal deviations from constant power and voltage output when driven by nominal wind and tower shadow effects.

Among the outputs of these analyses were the gains, frequency response characteristics and signal filtering requirements needed to design the control system electronics.

4.2 MODELLING

A simplified model configuration is shown in Figure 4-1.

Flow through the model starts with the wind, modified to reflect shear and tower shadow, impressed on the rotor. Blade torque uses a torque coefficient curve computation and hub torque depends on the blade response with flapwise and drive train flexibilities included. After drive train response, the generator dynamics produce an electrical power output relative to an infinite bus voltage phasor. Output power is used to get an error signal through the controller to modulate blade pitch angle with a wind feed forward signal added in. Generator excitation is modulated by voltage, acceleration, and reactive power level. When off line, speed is used as the variable to control blade pitch.

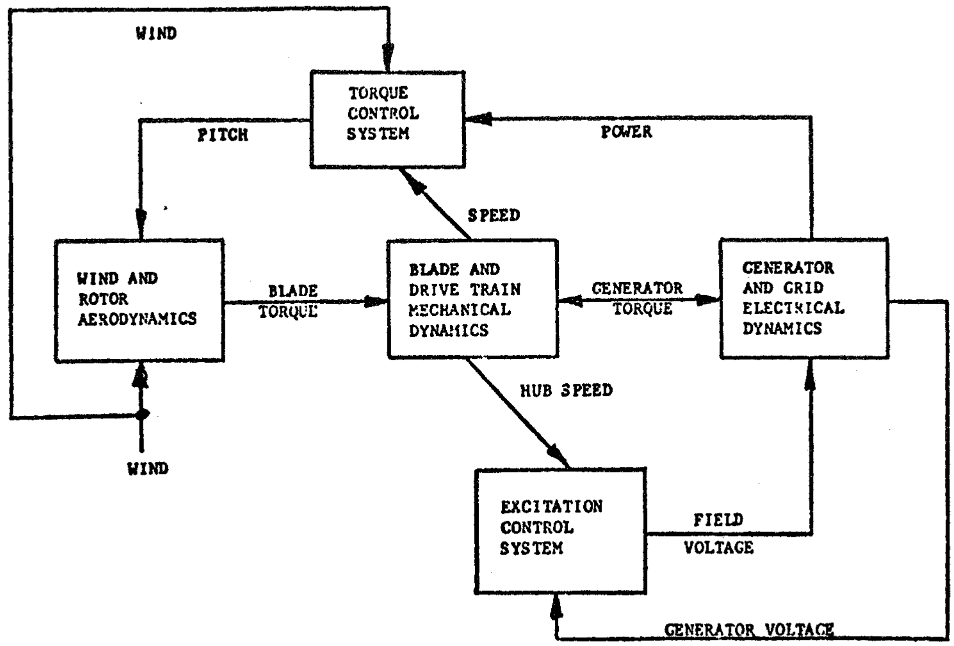

Figure 4-1. Basic Model Block Diagram

4.3 SUBSYSTEMS ANALYSIS CASES

4.3.1 FREQUENCY DOMAIN

Prior to defining wind and electrical transient load cases, inner loop and outer loop frequency domain analyses were performed. Small signal linearizations of the system variables about selected operating points were subjected to eigenvalue analysis to generate root locus plots and transfer functions.

4.3.2 TRANSIENT RESPONSE VARIABLES

To determine response for large, infrequently occurring transients, the following variations were made:

1.	Step Wind	.25 pu (per unit) step
2.	Continuous Frequency Wind	.2 pu at 2.5 rad/sec (.4 Hz)
3.	Step Voltage	.1 pu
4.	Random Wind	To .5 pu (peak-to-peak)
5.	Probabilistic Wind	0.1 percent gust (worst)
6.	Synchronization	On and off transients
7.	Emergency Overspeed and Speed Control Step	.8 pu step wind plus load loss

4.3.3 SMALL SYSTEM ANALYSIS

Frequency and 1-cosine time analyses were performed on a small network system. Voltage dips along the system and critical clearing time for a bus fault were analyzed.

4.3.7 SITE ANALYSIS

The effective site impedance to an infinite bus from the generator terminals is .05 + j.11 pu which represents a stable system connection at the low end of the range analyzed. Adjustment ranges are adequate to accommodate the site values.

4.4 COMPENSATION

4.4.1 FILTERING

In most loops, when a need to attenuate response at a particular frequency had been identified, a filter with second order zero and pole characteristics was specified to provide a "notch". This type of design is conventional and readily adjustable over a limited range via potentiometer and fixed resistance changes.

4.4.2 WIND FEED FORWARD (WFF)

The injection of a signal to control blade pitch angle at the same time a wind disturbance arrives at the rotor is a form of compensation. Data from Mod-0 at NASA Lewis Research Center's Plumbrook Station indicates a benefit with a single wind sensor in the range below 1 r/s (0.15 Hz), with analytical results predicting a benefit a decade higher. This is reasonable because the rotor responds to a much larger wind field and the sensor signal may represent local gustiness that does not affect the entire blade area.

On Mod-1, the average of two wind sensors is utilized as the control signal with computer controlled switching of the signal into the control loop. The WFF does not effect classical stability and in the nonachievable theoretical limit would provide constant rotor torque.

4.5 RESULTS

4.5.1 SPEED CONTROL LOOP

Response of the speed loop system, with gain at 20 degrees/radian, on the hybrid simulation to a loss of load from 1500 kW and shift to speed control resulted in an overspeed of 2.0 percent. A limiting-type condition which combines loss of load with a step increase in wind velocity from 50 to 90 fps at the hub results in a maximum overspeed of 10 percent.

4.5.2 EXCITATION SYSTEM

Responsive control of terminal voltage and use of the excitation system to improve drive train damping require a moderately fast response voltage regulator and exciter with forcing capability to aid transient stability for large torque changes. A Basler SRN4 voltage regulator is utilized with special modifications for adjustment of forward and feedback gains.

Response of the full simulation to a change in reference voltage at 1500 kW to a 1.5 percent step resulted in a voltage change of less than 2%. This closed loop loaded response includes saturation and is typical of an IEEE Type 2 brushless exciter and solid state voltage regulator system.

4.5.3 STABILIZER

Results were also obtained with a random wind input time response, with and without the stabilizer loop closed. A filter in the power controller loop attenuates response at the fundamental frequency to permit improved performance at all other frequencies, but this makes the power controller "blind" to this input frequency.

Quasi-resonant response buildups and decays are evident without the stabilizer due to the blindness. With the added stabilizer damping, however, the buildup is less and the decay is more rapid which provides reduced fatigue loading on the gearbox and smoother power.

4.5.4 POWER CONTROL AND COMBINED LOOPS

1-cosine disturbances in wind velocity for various combinations of control loops were examined. The behavior is consistent with frequency analysis. A need for additional filtering at 2P and 4P in the power control and stabilizer loops was identified to decrease aggravated response to tower shadow induced continuous perturbations.

4.5.5 TRANSIENT RESPONSE

4.5.5.1 1-Cosine Gusts

The most severe period 1-cosine gust that can be applied has a period around 2 seconds, or the same as the on-line fundamental frequency of oscillation. When this is applied to a system with stabilizers, but without wind feed forward control, significant power swings occur.

Action of the stabilizer is evident in rapid damping of power oscillations in the time after 3 seconds.

As gust period increases, the control system is more able to correct blade gain at the same time that wind changes occur and less transient system disturbance results. Variations in WTG terminal voltage and system voltage versus gust period are shown in Figure 4-2.

4.5.5.2 Step Gusts

Step response analysis produced the same general results as discrete 1-cosine gusts. The long time steady state pitch angle will change to accommodate the new wind at the reference power, but the transient is similar to that resulting from a small period 1-cosine input.

System response is characterized by the relatively low 2.5 r/s (.4 Hz, .7P) fundamental frequency and small 1-cosine inputs look the same as a square pulse or an up step followed by a down step.

4.5.5.3 Probabilistic Gusts

Synchronism was maintained for gusts with all control loops active and even without the stabilizer and wind feed forward. Removal of the power control loop (fixed blade gain) caused loss of synchronism for the worst 0.1 percent gust.

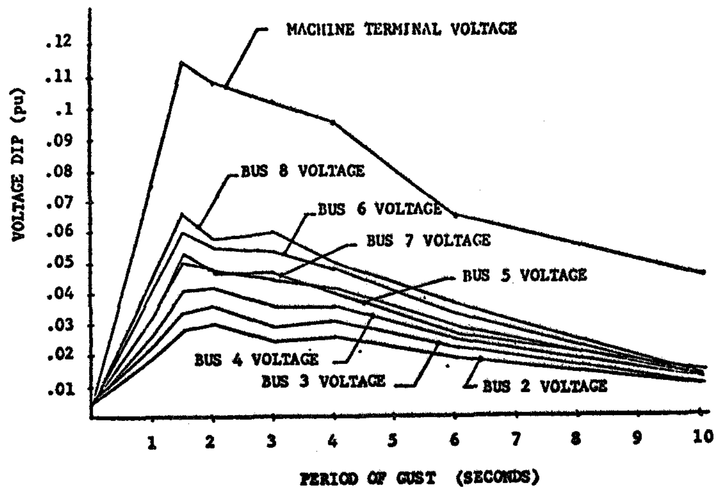

Figure 4-2. Voltage Dip Response

4.5.5.4 Random Wind

Long time response to moderate amplitude random wind resulted in variation in output power reduced to half the value resulting from not having wind feed forward. Wind field coherence variation was not modeled and site performance may not show as great a reduction.

Response to high amplitude random wind was examined without the power control loop energized to simulate fixed pitch operation. The stabilizer permited retaining synchronism for a short time, but a significant increase in wind velocity drove the generator out of synchronism with resultant circuit breaker opening and loss of load causing oscillations or "ringdown" of the generator inertia about the rotor due to the sudden removal of drive train torque. A lightly damped drive train model was used and site ringdown is expected to be better damped.

Voltage response at the generator terminals was generally within 5 percent on the .2 pu hybrid runs, although severe gust variations brought it as high as 10 percent. As the criteria is defined at a critical bus removed from the terminals, the derived requirement is satisfied for this system.

Variation in power is anticipated to be $\pm$ 30 percent for moderately gusty winds with all control loops active. Large gusts will excite a few swings of greater amplitude, possibly reaching $\pm$ 100 percent. Constant wind produces $\pm$ 6 percent power response due to tower shadow.

4.5.5.5 Emergency Feather

A series of loss of load and step gust cases were simulated with various programmed pitch change rates in order to evaluate operation of the emergency feather system. Too rapid a change in pitch angle creates large decelerating torques that are undesirable from a blade-to-tower clearance standpoint. The results of a rate schedule with initial value at 14 degrees per second, then shifting to 2 degrees per second after 1.5 seconds, then further shifting to speed control at 80 percent of speed showed acceptable speed variation.

SECTION 5

MECHANICAL SUBASSEMBLIES DESIGN

SECTION 5

MECHANICAL SUBASSEMBLIES DESIGN

5.1 BLADE

The Mod-1 WTG incorporates two blades in its rotor system, each of which is mounted to the hub via a pitch bearing and is capable of being controlled collectively in pitch by the pitch control mechanism.

5.1.1 DESCRIPTION

Each blade is 97.5 feet long, tapered in planform and thickness as shown in Figure 5-1. It utilizes a NACA 44XX series airfoil with thickness ratio varying from 33% at the root to 10% at the tip. The twist of 11° varies linearly from root to tip.

The major load carrying member is a hollow steel spar. It is fabricated from A533 Grade B, Class 2 high strength, low carbon steel. The spar is assembled from upper and lower panels, each panel welded in six sections approximately 180 inches long. The lower panel, which sees compression loads, is stiffened by chordwise intercostals and a spanwise tee-shaped stiffener.

The trailing edge is fabricated from urethane foam with 301 stainless steel skins. Foam blades are bonded together, each block varying in density according to load requirements. Adjacent to the spar, foam-in-place application provides a continuously adhered joint between the spar and trailing edge sections.

5.1.2 PERFORMANCE CHARACTERISTICS OF THE MOD-1 (BOEING) BLADE

The selected blade geometry is a compromise between aerodynamic performance and ease of fabrication. Although airfoil sections such as the LS (1) would have provided higher performance, the 44XX series was selected because it does not have a concave lower surface. At rated wind speed a power capture of 1855 kW_e was computed, based on the blade performance shown in Figure 5-2.

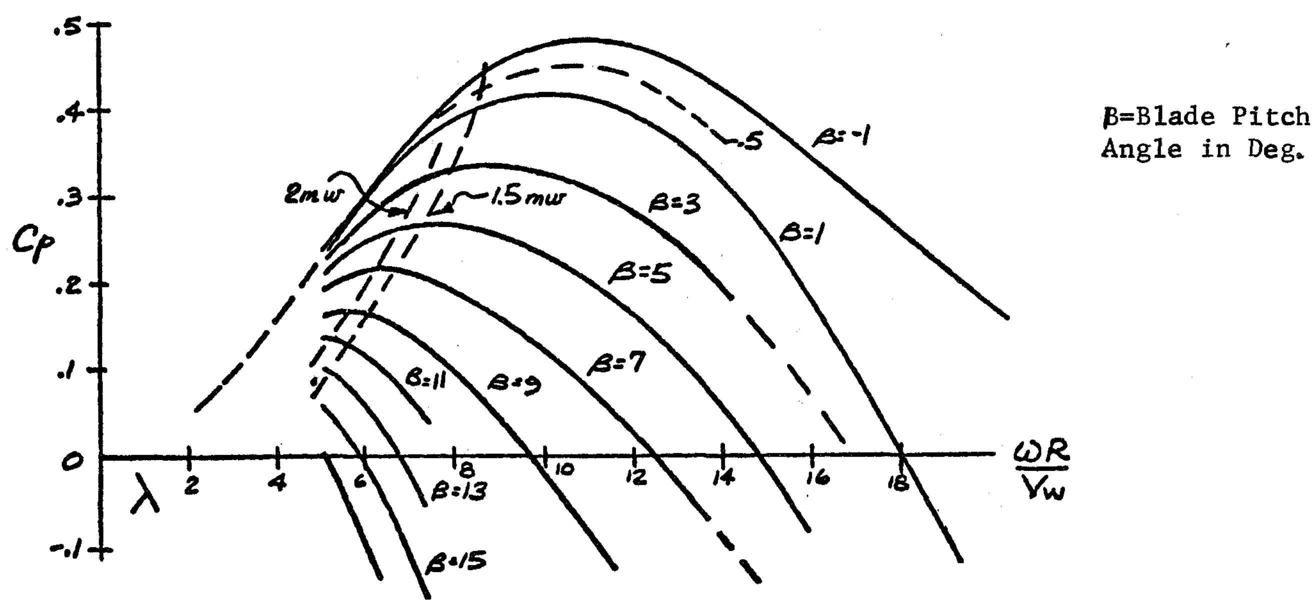

Figure 5-2. Wind Turbine Performance

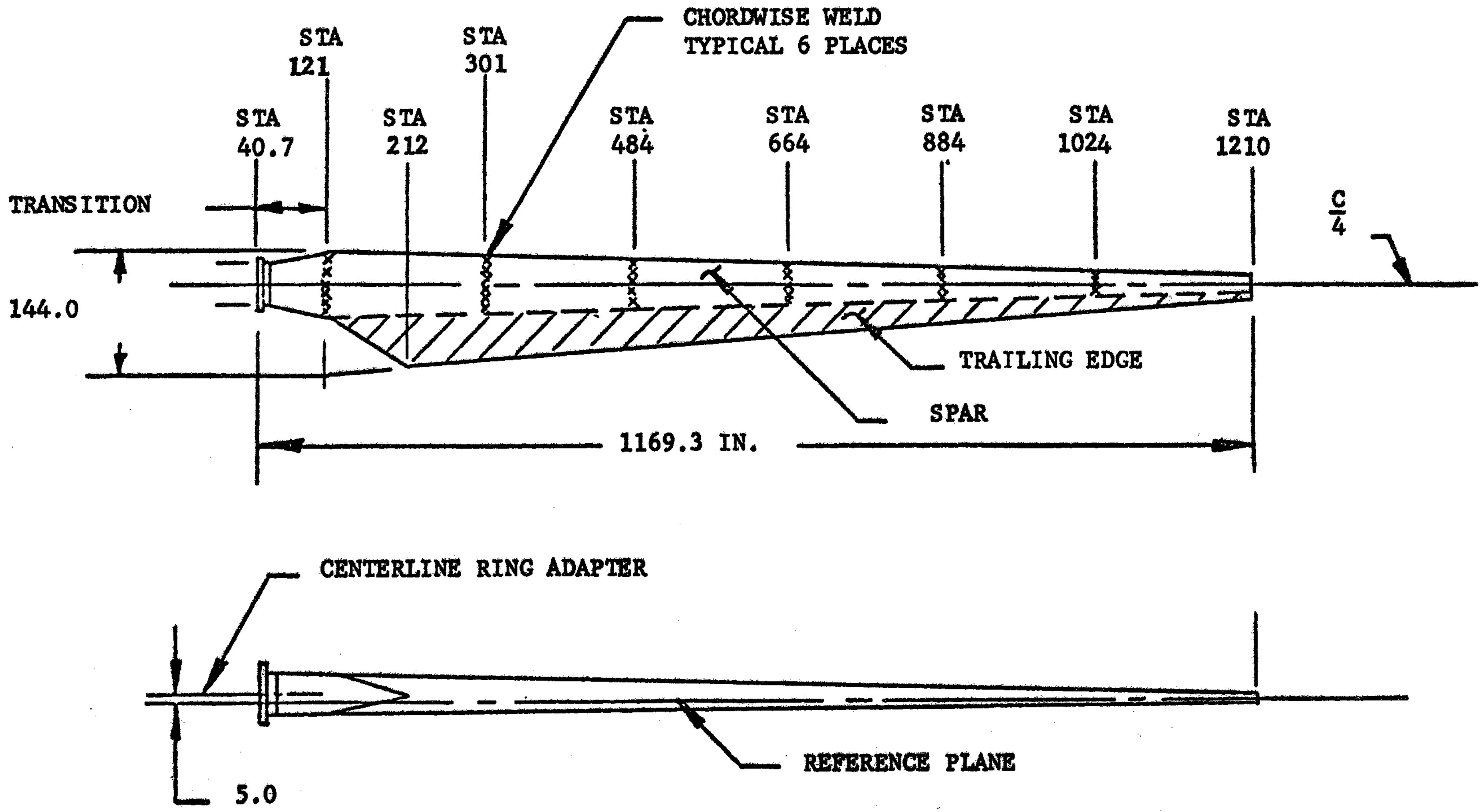

Figure 5-1. **Blade Geometry**

5.2 ROTOR HUB

The rotor hub is all bolted construction, thereby avoiding the range stress limitations placed on weldments. Thus the structural requirements for the rotor hub are that the fatigue stresses not exceed the endurance limit for the material, and that peak operating loads, or other functional loads, will not cause stresses that exceed the allowable stresses specified in the AISC code.

The rotor incorporates a lock designed to hold the blades either vertically or horizontally. It is capable of holding the rotor from turning when feathered in the 6-12 o'clock position against a broadside 50 mph wind, including wind shear. This is a "worst case" condition that could result if there is a failure of the parking logic to put the blade in the 3-9 o'clock position.

5.2.1 HUB

The hub carries the rotating blades and reacts the loads to the fixed bedplate. The hub consists of a cylindrical barrel with end rings at 9 degrees for blade coning. See Figure 5-3. The wall thickness of the barrel varies uniformly, and becomes thickest at the joint with the tailshaft. The tailshaft joins the barrel with a 120 degree saddle flange and a transition to the circular main bearing seat and flange. Both parts are machined from carbon steel forgings, ASTM A266, Grade 2. Fasteners around the joining flange are closely fit to transmit shear. Studs are installed through the circular flange. Bolts are used around the perimeter of the joining flange and along the straight flange. The forward end of the tailshaft is closed by the torque plate which secures the main bearing inner race and transmits rotor torque to the smaller drive shaft coupling flange. The torque plate is machined from steel plate of ASTM A516, Grade 70 (as are all other parts unless noted otherwise) and is fastened to the end of the tailshaft with 42 studs. Clearance between the end of the tailshaft and the torque plate is shimmed so that a tension load equal to 44% of the stud's yield strength closes the gap to clamp the bearing. Further tension to 88% of yield strength provides the clamping friction for the driving torque. The connection to the drive shaft coupling is with 22 studs. The outboard surface of the barrel has an access hole with a gasketed cover plate. Holes in either side of the barrel, the lowest point when the rotor is at the feathered position, allow condensate to drain.

All bolts and studs for the blade attachment through the tailshaft joint have UTS of 180,000 psi because of the substantial alternating loads. The torque plate bolts are to ASTM A490 (150,00 psi).

5.2.2 BLADE INTERFACE AND RETENTION BEARING

The blade retention bearing is a 3-row roller bearing with one inner and two outer races made of AISI 4150 steel. The roller paths are case hardened and 56 axial holes through the races are provided for attachment. The three rows of rollers are all of different size to accommodate the loading; the thrust row that carries blade moment and centrifugal force is the largest, and the radial row is the smallest. Because of the limited rotation, the bearing is grease lubricated with feed points at 8 places on each of the roller rows. The lubricant is applied at one point on the forward side of the torque plate.

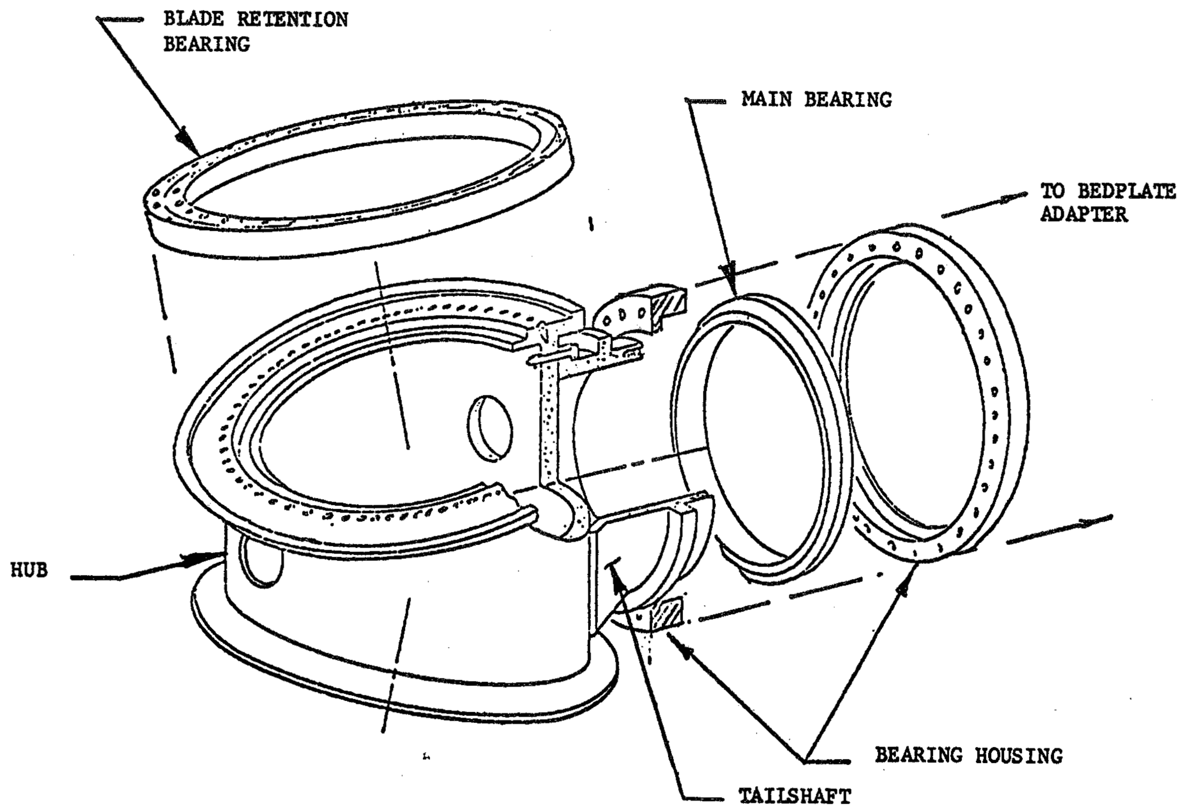

Figure 5-3. Rotor Hub

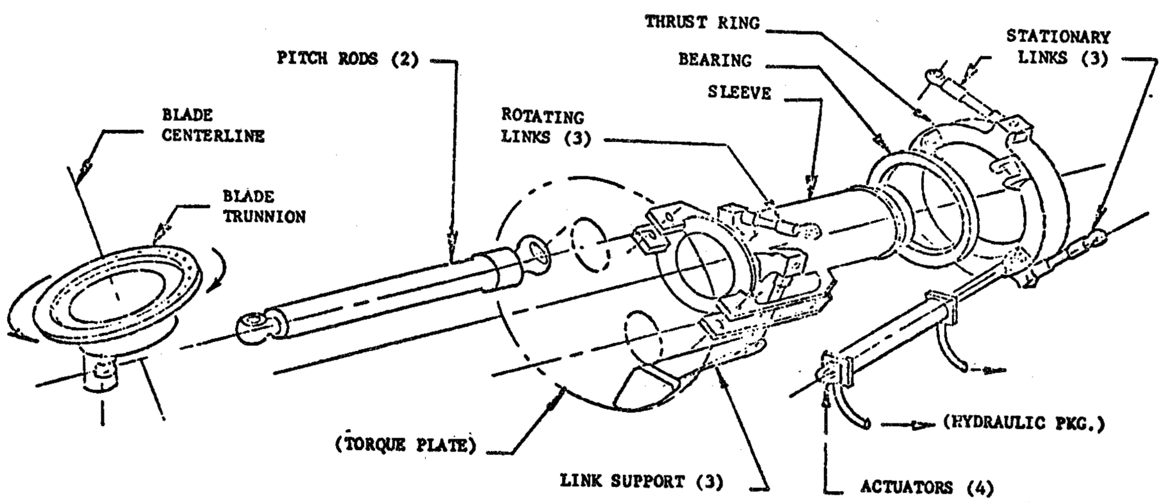

Figure 5-4. Pitch Change Mechanism

Two stages of volumetric distributors connected by steel tubing distribute the grease equally to 48 points on the two bearings. Studs secure the bearing to the hub barrel and bolts secure the piloted blade flange to the bearing.

5.2.3 MAIN BEARING

The single main bearing is a two-row angular contact roller bearing with a high contact angle of 45 degrees. The two separate inner races and the single outer race are made of AISI 52100 through-hardened steel. The inner races are a shrink fit on the tailshaft. The inner races are clamped axially by the torque plate. The two housings clamp the outer race and are held together by 8 bolts until the bearing is attached to the bedplate rotor adapter.

The high contact angle caused high end load of the rollers against the inner race. The induced friction heat load is more than grease can accommodate so oil lubrication is required. The lubrication system draws oil from the speed increaser gearbox, and it is used to lubricate and cool the main bearing.

The flow is divided and 15 gallons per minute is fed to 6 points in the upper side of the outer race. An annular groove distributes the oil to radial holes through the outer race. The oil passes through the roller paths and extracts heart from the races and rollers, then it collects in the bottom of the bearing housing. A scavenging pump withdraws the oil at the rate of 17 to 18 gallons per minute. The rotating shaft is sealed by three elastomeric lip seals on each side running on a nickel-iron weld coating on the hub flange and torque plate. The two inner seals have spring fingers to assist in retaining the oil. The outer seal without spring fingers keeps debris out. Grease is injected at four circumferential points between the middle and outer seals to lubricate them and catch external debris. Grease for the forward and aft sides of the seal is piped separately but both grease input points are accessable from within the nacelle.

5.3 PITCH CHANGE MECHANISM

5.3.1 Suspension

The suspension transmits the force and motion from the stationary actuators to the rotating blades. This element must have motion limited to one axis, while other directions are restrained. The suspension consists of two sets of 3 links each. The forward set supports the nonrotating outer race of the bearing from the bedplate, while the aft set supports the rotating inner race from the torque plate through cantilever beams. Corresponding ends of each set of links lie in a plane perpendicular to the direction motion, e.e., rotor Z axis. The links of a set are equidistant and tangential to the element it supports. As the moving element is displaced axially, it rotates about that axis in a varying helical motion. If the ends of the links are planar, equally spaced, and equidistant from the axis, the motion is concentric.

Displacement of the mechanism from the axis of rotation may result from axial displacement due to position errors of the ends of the links. Displacement of one end of the mechanism in a direction different from the other will cause differential blade pitch change. This change, with reasonable assembly tolerances is less than .05 degrees in the operating range and is insignificant.

5.3.2 Actuator Sleeve

The actuator sleeve is a weldment of steel pipe, ASTM A106, Grade 2, and end rings. The two pitch rod fittings are attached to the aft end with studs. The three lugs for the aft swing links are near the aft end. The pitch change bearing, is a double row tapered roller bearing similar to the main rotor bearing. The thrust ring is machined from plate and holds the outer race of the bearing. Both races are clamped by end rings. The four clevises which connect to the rod end of the actuators are bolted to the aft face of the thrust ring. Each side of the bearing is protected by two elastomeric lip seals. Grease lubricant is injected into nine radial passages through the thrust ring, and is further distributed around an annular groove in the outer race and through radial holes into the roller paths.

5.3.3 Links

The swing links that suspend and guide the actuator sleeve are identical forward and aft. They consist of a 4340 steel bar internally threaded at both ends. Rod end bearings screw into the link with a retaining nut on the rod end shank. Two set screws lock the nut, while a bolt through the link and rod end is the key that prevents rotation of the rod end. Bearing inserts consist of a stainless steel ball turning in a woven TFE liner. These bearings require no lubrication.

The pitch rods consist of 4340 steel bar with internal threads, opposite threads at each end. The end of the rod at the actuator sleeve receives a differential threaded nut into which a rod end bearing is threaded.

The length of each rod may be varied by half turns of the differential nut. The adjustment of the rod length allows each blade to be adjusted over approximately 3.8 degrees in 0.14 degree increments from inside the nacelle.

5.4 DRIVE TRAIN

The drive train begins with the rotor tail shaft and the mating flange on the low speed shaft, continues through the gearbox, slip clutch, and ends at the interface between the high speed shaft and the generator. Included in this definition is the rotor brake and the lubrication system.

5.4.1 FLOATING SHAFT ASSEMBLY (LOW SPEED)

Connecting the rotor to the gearbox is a floating shaft assembly, consisting of a drive shaft with flexible couplings mounted on each end. Flexible gear hubs are mounted on each end of the drive shaft and mate with a rigid flange on the rotor and a rigid hub on the gearbox, allowing the shaft to accommodate angular and lateral misalignments as well as axial float. Angular misalignment is limited to 1/2 degree per engagement plus a parallel off set of 0.50 inch.

The ends of the drive shaft are tapered to permit hydraulic mounting or removal of coupling hubs. An interference fit of approximately 0.002 inch per inch diameter permits full torque transfer without the stress concentration of a keyway.

5.4.2 SPEED INCREASER GEARBOX

The gearbox is a three-stage, tandem articulated, parallel shaft unit with input and output shafts on a vertical centerline, and horizontal casing splits. The tandem articulated shafts permit the load path to be split with equal sharing of the load. The gearing is designed for strength and durability for 30-year life to AGMA specifications with periodic maintenance.

The low speed stub shaft is tapered for keyless mounting and hydraulic removal of a rigid hub and has a 6-inch internal bore for passage of cables from the rotor to a slipring assembly, which is bolted to the face of the shaft extension on the upwind side of the gearbox.

Bearings and gears are lubricated by an electric pump-driven spray system. The pump has sufficient excess capacity to supply lubricating oil to the rotor bearing also. The gearbox incorporates internal heaters in the sump for start-up at low temperatures.

5.4.3 HIGH SPEED SHAFT ASSEMBLY

The high speed shaft assembly includes the high speed brake disk, a slip clutch and a floating shaft that connects the speed increaser gearbox to the generator. A toothed wheel bolts to one face of the rotor brake disk; it provides the means to sense the rotational speed of the shaft electromagnetically. The slip clutch provides overload protection for the entire drive train by slipping when torque exceeds 188% of rated torque, or 15,400 ft-lb. The slip clutch is the dry type with metallic friction plates, adjustable for torque level by means of adjusting bolts.

The two flexible half couplings, separated by a floating spacer shaft, accommodate both angular and offset misalignment between the gearbox and generator. Thrust plates and buttons on the spacer limit axial float which is limited because of the lack of thrust capability in the generator bearings. The spacer is removable by unbolting flanges at each end.

5.4.4 ROTOR BRAKE

The brake used to bring the rotor to a stop and position the blades in a 3-9 o'clock position, consists of a stainless steel disk mounted on the high speed shaft and a hydraulically operated brake caliper attached to the gearbox housing. The brake caliper is a standard unit made by the Goodyear Corporation, Berea, Kentucky, for off-road vehicles. The brake disk was made from stainless steel to avoid the possibility of irregular operation caused by rust build-up during non-operating periods, as experienced on Mod-0.

5.5 NACELLE

5.5.1 BEDPLATE

The final bedplate design differs considerably from the concept originally presented at the Preliminary Design Review. This is a result of a change in the design approach that occurred during the early stages of final design definition. The concept originally presented was a complex truss, composed of standard rolled sections (mostly wide flange I beams) of A36 low carbon steel. As the detail design progressed, it became apparent that this concept presented several problems.

As a result the bedplate was reconfigured to a box girder type construction, using plate forms for all but a few secondary details. A516 Grade 70 steel was chosen, a material with good impact strength at low temperature, and less vulnerable to poor welding characteristics that sometimes occur as a result of the liberal chemical composition limits of A36. The plate design did not reduce the amount of welding required, but more of the welds could be accomplished as a continuous pass and could be categorized for higher allowable stresses. Since the configuration more closely resembled the box girder construction commonly used in bridge construction, it became easier to identify the appropriate weld joint category according to AISC fatigue requirements (which are based largely on bridge construction). Optimization and design changes could be incorporated more easily by changing only the plate thicknesses without redefining the basic geometry.

5.5.2 LUBRICATION AND ENVIRONMENTAL CONTROL

The lubrication oil system provides lubricant for the rotor bearing as well as the gearbox. The system is required to maintain a sufficient flow of oil within an acceptable viscosity range of 340 to 5,000 SUS at all operating temperatures. During startup when ambient temperatures are below 55°F, the oil must be heated and circulated before rotation can begin; at oil temperatures above 150°F, the oil must be cooled by circulation through an external cooler.

The environmental control system, operating in conjunction with the oil lubrication system, is required to maintain the air temperature within the nacelle within acceptable limits. The most sensitive equipment within the nacelle is the nacelle multiplexer unit, which must operate within an ambient air temperature of 0° to 130°F. The generator draws cooling air from within the nacelle and exhausts externally, utilizing a built-in fan.

5.5.3 YAW SUBSYSTEM

The primary requirement of the yaw subsystem is to position and align the nacelle assembly with the wind velocity vector. Changes in the wind direction would require the YS to follow the wind by repositioning the nacelle/rotor accordingly. The YS also provides the structural interface and transition between the top of the tower and the rotating bedplate. Another function is automatic relief from rotational overload conditions that may occur from sudden changes in wind in-flow angles.

During shutdown periods and non-maneuvering modes, six brakes are engaged in a static configuration that produces a holding force of 2.1×10^6 ft-lb. at an applied pressure of 3,000 psi.

Figure 5-5 shows a simplified schematic of the hydraulic pressure system. Hydraulic power from a central source is used to service three areas: 1) yaw drive motors, 2) yaw brakes and 3) high speed shaft brake. The requirements for operating the motors differ from the two brake systems since a closed loop servo system controls the motor functions, and a displacement fluid system operates both brakes.

5.5.4 PCM HYDRAULIC SYSTEM

The function of the PCM Hydraulic System is to provide the actuation to the pitch change mechanism and to permit feathering of the blades during an emergency situation.

The emergency feather control permits slewing control flow to pass from the servo valve to the accumulators without restriction. In an emergency, (or on command), the emergency feather control blocks the servo valve, by closing the block check valve and the feather lock valve, opens the feather dump valves and the feather valve. Opening the feather valve admits hydraulic fluid to the blind end of the actuators, precipitating actuator movement in the direction to feather the blades. Hydraulic fluid from the rod ends of the actuators is permitted to return to the hydraulic reservoir via the feather dump valve. Two separate, but identical, circuits are provided in the emergency feather control to assure reliability. Each circuit serves two actuators. Each actuator pair is capable of independently accomplishing blade feathering. The four-part, two-way feather solenoid valve in each circuit controls the piloted check valves. Hydraulic flow through each circuit is provided by two pairs of accumulators, each pair dedicated to a pair of actuators.

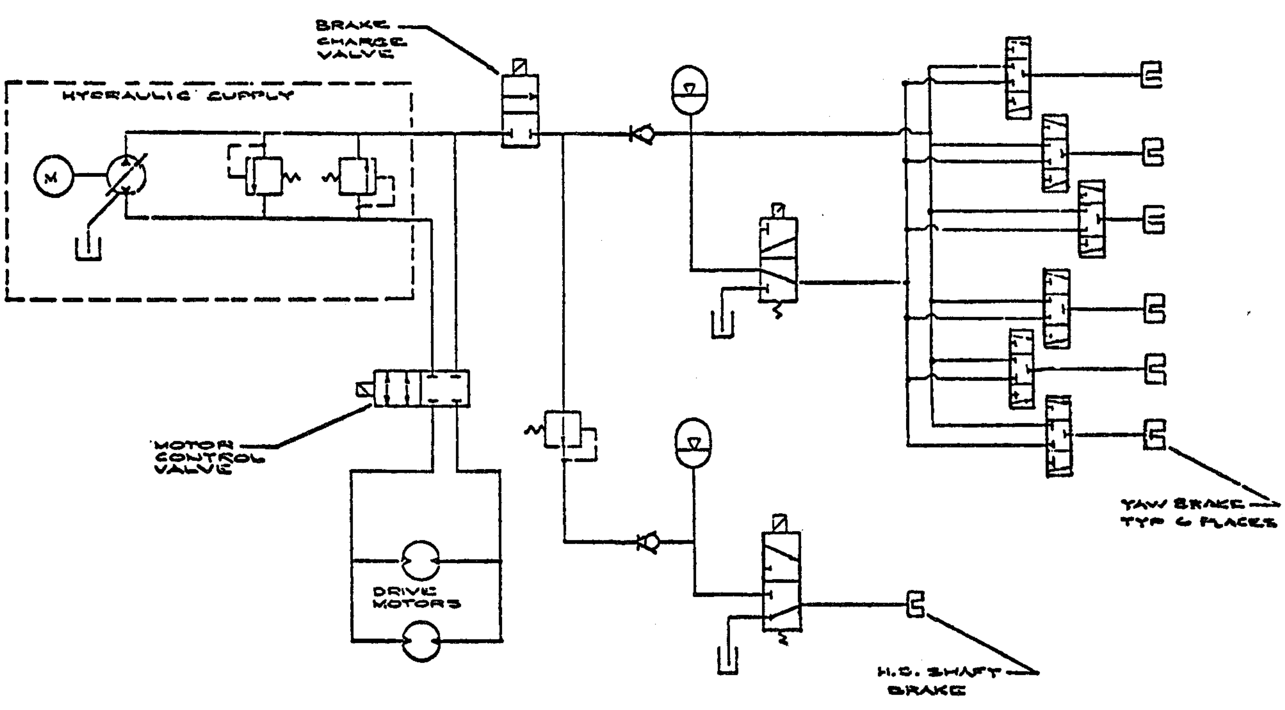

Figure 5-5. Yaw Hydraulic Pressure System Schematic

5.6 TOWER

5.6.1 REQUIREMENTS

The design requirements for the tower specified in the NASA Statement of Work can be summarized as follows:

1. Open truss construction with members of structural carbon steel.
2. Bracing generally designed for bolted field assembly.
3. Provide a lift device of half-ton capacity for access to the nacelle.
4. Provide a means for evacuation of personnel in the event of failure of the lift device.
5. Maximum design wind load of 150 mph.
6. Seismic loads per Zone 3.
7. First bending frequency shall be at least 2.8 times the rotor operating frequency.
8. First torsional frequency shall be at least 6.5 times the rotor operating frequency.

In addition, the tower is required to have a design life of 30 years, operating in a range of environmental conditions, including temperature extremes from $-31^{\circ}F$ to $+120^{\circ}F$. The low-temperature requirement is significant because it places the fracture-toughness requirements for the steel in the most severe class, Zone 3.

Comparison with loads determined by the system dynamic simulation has shown that the critical design conditions are Case A for fatigue and Case B for peak stresses, rather than the hurricane wind loads or seismic loading defined in the SOW.

5.6.2 DESIGN DEFINITION

During the detail design phase, the tower design evolved through several iterations in an attempt to satisfy strength and stiffness requirements at minimum cost, in the face of continual growth in system weight and design loads. As part of this design evolution, several trade-off studies were made on the selection of overall geometry, grade of steel, and structural form of members. To gain maximum bending stiffness, the tower height was reduced and the width increased as far as adequate blade clearances would allow. Beyond that point, it would have been necessary to introduce a tilt in the rotor axis or increase the rotor overhang in order to maintain clearance with the tower when the blade is at its maximum tip deflection. Having established the overall geometry, the only parameter to be varied to achieve the desired strength and stiffness was cross-sectional area of the primary members.

For the four tubular leg members that comprise most of the tower weight, the selection of steel grade became a tradeoff between fracture toughness and cost.

Pipe of the required diameter and wall thickness is normally available to a limited number of specifications. The two candidate materials for the tower

were ASTM specifications A53 and A333. A333 has good, well-established fracture toughness but is higher in cost than A53 when compared for Zone 1 service temperatures (0°F and above). However, for Zone 3 service, the cost difference becomes uncertain. Suppliers are unwilling to guarantee the results of Charpy V-notch tests on A53 pipe because of the latitude in chemical composition of steel to this specification. Experience with bridge failures due to brittle fracture has led AASHTO (American Association of State Highway and Transportation Officials) to specify the test temperature for standard impact tests with steels similar to A36 at 70°F above the intended service temperature. For Zone 3 (-31 to -60°F), toughness must exceed 15 ft-lb at a test temperature of 10°F. A333 would have no difficulty meeting this requirement while test results for A53 would be marginal and only selected heats would be expected to pass. Thus A333 was selected.

Tubular members for the tower were specified because of their low drag coefficient as compared with other structural shapes. The objective was to keep the velocity decrement in the tower wake acceptably small, and to have confidence in the estimate of tower shadow by being able to relate it to wind tunnel measurements for all-tubular tower models and other data.

SECTION 6

POWER GENERATION SUBSYSTEM

SECTION 6

POWER GENERATION SUBSYSTEM

6.1 SYSTEM DESCRIPTION

A simplified one-line diagram of the basic power circuit is shown in Figure 6-1. The utility connection with Blue Ridge Electric Membership Cooperative (BREMC) is stepped up from 4.16 kV to 12.47 kV. Auxiliary power is obtained from the 4.16 kV bus through transformers to 480 and 208Y120 Volt distribution systems. The generator is connected or disconnected from the 4.16 kV bus depending on whether or not the wind is blowing.

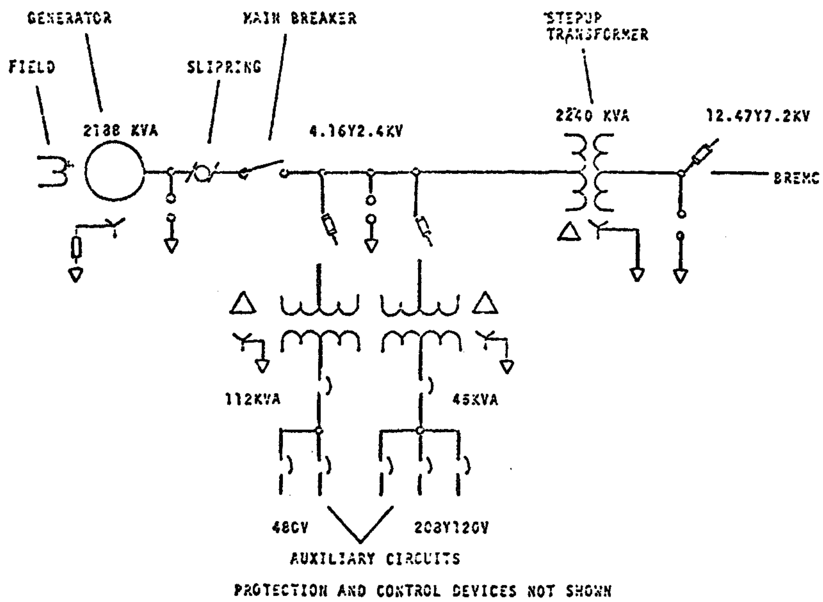

Figure 6-1 Simplified One-Line Diagram

The generator and associated exciter, sensing and protective devices are located in the nacelle. An auxiliary control and power distribution box, several discrete sensors, and the nacelle multiplexer unit (NMU) are interconnected and wired to the tower slip rings which provides for yaw rotation.

On the tower side of the slip ring, conduit enclosed wiring runs to the control enclosure at the base of tower. The enclosure houses the remainder of the control system, the generator main breaker, additional sensing and indicating devices, and the auxiliary power transformers and distribution. A separate pad is located under the tower for mounting of the Generator

Step-up (GSU) Transformer which connects to the enclosure and to the BREMC.

The individual elements of the Wind Turbine Generator system are described in the following paragraphs, and shown in the block diagram, Figure 6-2.

6.2 GENERATOR AND POWER GENERATION AUXILIARIES

The generator, is a 4-pole, 1800 rpm, 4160 Volt, Wye connected unit with shaft-mounted exciter. Class F (105°C rise over 40°C ambient) insulation is used. The generator is rated 2188 kVA, .8 power factor and the exciter is rated at 25 kW at standard ambient.

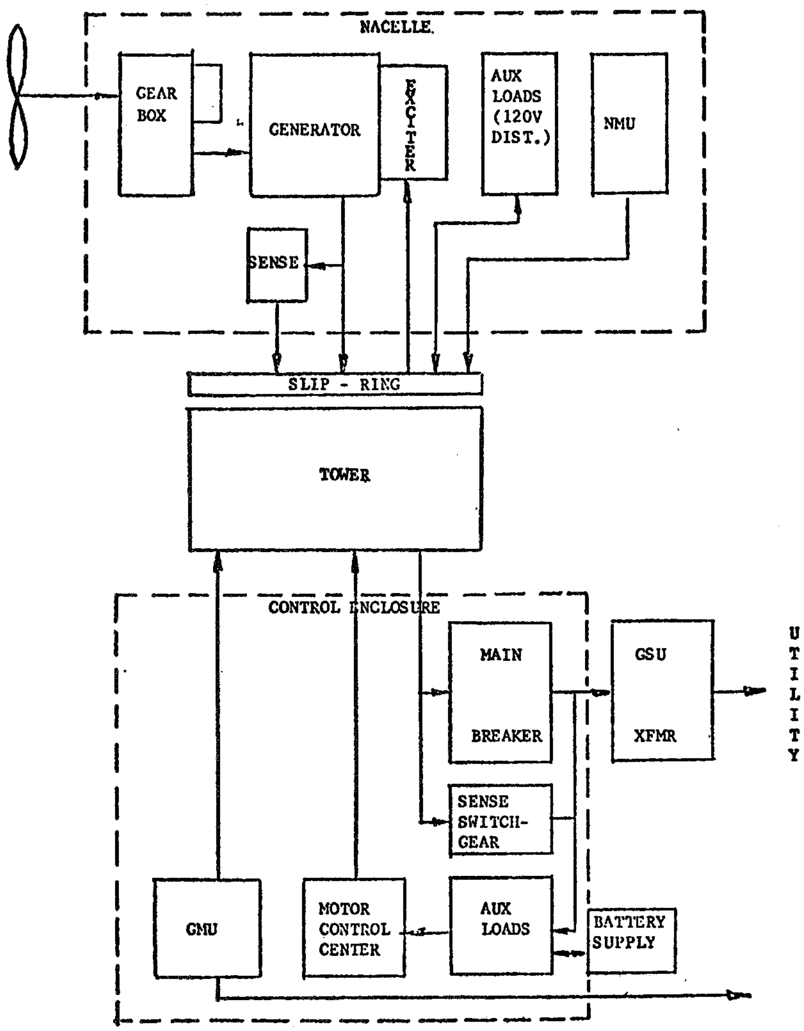

Figure 6-2. Mod-1 WTG Block Diagram

Auxiliary equipment is mounted in a caged area under the generator and consists of primary winding protective lightning arrestors and surge capacitors, a potential transformer, neutral side mounted current transformers, and a grounding transformer. The all six generator leads are brought out in order to mount the phase current transformers. A grounding resistor associated with the transformer is mounted on top of the generator.

6.3 <u>SWITCHGEAR AND TRANSFORMER</u>

6.3.1 ELEMENTS OF SWITCHGEAR

Switchgear for control, protection and instrumentation of the system are mounted in the control enclosure and consist of:

1. Generator Circuit Breaker and Isolation Switch
2. 4160 Volt Bus and Protection Equipment
3. Instrument Transformers
4. Protective Relays
5. Transducers for signals to Data Systems
6. Auxiliary Power Supply Transformers
7. Main Protection for Auxiliary Power Supply
8. Terminations for High Voltage Cable
9. Grounded Metallic Enclosure
10. Visual Indicating Instruments
11. Generator Control Devices

6.3.2 GENERATOR CIRCUIT BREAKER AND ISOLATION SWITCH

The generator circuit breaker 52G is based on a large motor starter rated at 4160 Volts, 360 Amperes continuous, with 50 mVA interrupting capability without fuses.

6.3.3 POWER EQUIPMENT

An insulated bus structure is provided for the line side of the contactors. The bus connects to the step-up transformer by cable and connects to the auxiliary supply transformers, potential transformers, and lightning arrestors in adjacent compartments. As previously noted, the generator connects to the "load" side of the contactor.

6.3.4 SWITCHBOARD

A freestanding cabinet houses the protective relays, generator excitation equipment and instrumentation transducers and indicating devices.

Internal generator faults are detected with the field energized before the main 52G circuit breaker is closed due to the current transformer placement, and operation of the 51V over current relay effectively causes lockout of the system for a cable fault between the generator and main contactor. The output contact wiring goes to the 94G trip relay.

Transducers with current source output are mounted in the switchboard to provide isolated signals to the operational and engineering data system. The indicated quantities are:

1. Utility frequency
2. Real power
3. Reactive power
4. Three-phase utility voltage
5. Single phase generator voltage
6. Three-phase primary current
7. Single phase auxiliary current
8. Exciter field current

Indicating DC milliameters with appropriate scales are provided for the transducers. Conventional utility practice is to provide a switch for most meters in order to read currents and voltages on only two meters by switching between phases. This practice reduces panel space and provides a slight cost saving. Panel space is not critical on the Mod-1 WTG, and three meters are provided, each for voltage and current, to minimize manual switching.

Watthour meters are provided for the main generator circuit and for the auxiliary power circuit. They back up the minicomputer totals kept on the same quantities. The indicating instruments and scales consist of:

1. Real Power - Kilowatts (-500/0/+2500)
2. Reactive Power - Kilowatts (-500/0/+1500)
3. Voltage - 3 Phases (0-6 kV) plus 1 phase generator (0-6 kV)
4. Current - 3 Phases (0-300A)
5. Current - Auxiliary (0-20A)
6. Synchroscope - Utility to generator
7. Frequency - (55 - 65 Hz) Utility and Generator
8. Power Factor - (-0.6/0/+0.6)

6.3.5 TRANSFORMER

The generator step-up (GSU) transformer provides voltage matching between BREMC 12,470-Volt distribution and the WTG 4160 Volt system. An oil-filled distribution type unit with accessories in air insulated connection compartments is utilized with 2,000 kVA and 2240 kVA ratings at 55°C and 65°C rise respectively.

A grounded wye connection is utilized on the BREMC side to limit line-to-ground potential imposed on the system. Lightning protection is provided for the transformer and a fused interlocked manually-operated air switch provides disconnect capability. A line-side neutral current transformer is provided to sense line faults.

The secondary is Delta connected. A no-load tap charger and four primary taps, each 2.5 percent apart, are provided.

Accessories provided with the transformer include:

1. Resealing fault pressure vent
2. Ground pad
3. Handhole
4. Oil sampling device mounted on drain valve
5. Liquid level gage with alarm contacts
6. Temperature gage with alarm contacts
7. Anti-condensation heater
8. Key interlock on high-voltage fuse compartment

6.4 AUXILIARY POWER DISTRIBUTION

6.4.1 LOAD BUSES

480 Volt, Three Phase - A 112.5 kVA, 3-phase transformer is used to supply a 480 Volt bus. The principal loads on this bus are:

1.	Pitch change hydraulic pump	20 hp
2.	Pitch slew hydraulic pump	20 hp
3.	Yaw and brake hydraulic pump	20 hp
4.	Gear and rotor lube pump	15 hp
5.	EDAS PIV	30 kVA

208/120 Volt - A 45 kVA transformer supplies a 3-phase, 208 Volt bus that is also utilized to supply 120 Volt single phase loads by line to neutral connections. The principal loads are:

1.	Nacelle 120 Volt power distribution	10kVA
2.	Scavenge pump	3 hp
3.	Oil cooling fan (if required)	10 hp
4.	Lift and gearbox heaters	8 kVA
5.	Control enclosure 120 Volt power distribution	15 kVA

6.4.2 PROTECTION AND CONTROL

A factory-wired motor control center is utilized for branch circuit protection and control.

6.5 STATION BATTERY

A 50-Ampere hour, 125-Volt lead calcium station battery assembly with charger is provided in an insulated and heated enclosure mounted on the outside wall of the control enclosure. The dc supply provides tripping power for the main breaker, operates assorted relaying the the switchboard, and powers the aircraft warning lighting. A float charge at 2.12 Volt dc per cell is maintained to eliminate equalizing the battery periodically. The charger has a 9 Ampere continuous supply capability and is powered by a single phase 208 Volt ac supply.

Due to lack of room in the control building and to eliminate the concern for possible hydrogen collection, the batteries are mounted in an outside cabinet. The cabinet is a two-tiered device, providing access to all the cells and charger for ease of maintenance.

6.6 SLIP RINGS

The yaw slip ring assembly handles the electrical interface for all wire and cables between the nacelle and ground or tower. A position sensor gives the relative position between the tower and the nacelle.

The rotor slip ring assembly is located on the gearbox in the nacelle, driven by the low speed shaft, which brings out rotor instrumentation leads. An angular position sensor is built into the assembly as a means of determining the rotor position.

6.7 LIGHTNING PROTECTION

The most probable lightning events are direct strikes on the WTG structure or electrical circuit incoming voltage surges due to strikes on the overhead distribution lines.

Minimum earth resistance is specified at less than 5 Ohms and is provided by two wells drilled 15' below the local water table at the site. Each tower leg is tied to the rod arrangement and bridging straps are used at the main leg joints.

The blade, hub, and yaw bearings are potential current carrying paths for a lightning strike and are protected with an outer diameter located gap which will break down and carry most of any large discharge current due to the high rate of rise of current and inductive path through the bearing proper.

The lightning model specified has an initial peak current of 200 kA at a rate of rise of 100 kA/microsecond. Most data available indicates 100 kA or more peak is reached only 2 percent of the time and that a 50 percent probable value is about 20 kA. Intense local heating will occur where the streamer strikes the structure but only superficial damage is expected.

A Faraday cage effect is present for equipment within the nacelle and local potential differences should not occur unless the current path is badly asymmetric. Since a strike on a tower leg will introduce some "near-strike" electromagnetic coupling into conduit enclosed wiring, optical isolators have been applied to sensitive circuits. Low-voltage motors are not protected as their insulation level is normally adequate to survive surges unless directly connected to an overhead line.

The higher voltage apparatus is more sensitive to steep front surges due to larger size and capacitive division of a large percentage of the surge onto the first winding section. A lower ratio of test-to-normal voltage exists and lightning arrestors are applied at the BREMC terminals within the control enclosure at the 4,160 Volt bus, and at the generator terminals. A surge capacitor is also mounted at the generator terminals. This protection is deemed adequate for strikes on the incoming line or induced "near-strike" surges.

6.8 CONTROL ENCLOSURE

A van-type enclosure, is used to house ground-mounted equipment. The interior arrangement is shown in Figure 6-4 with control electronics equipment mounted at one end and power equipment at the other to minimize EMI.

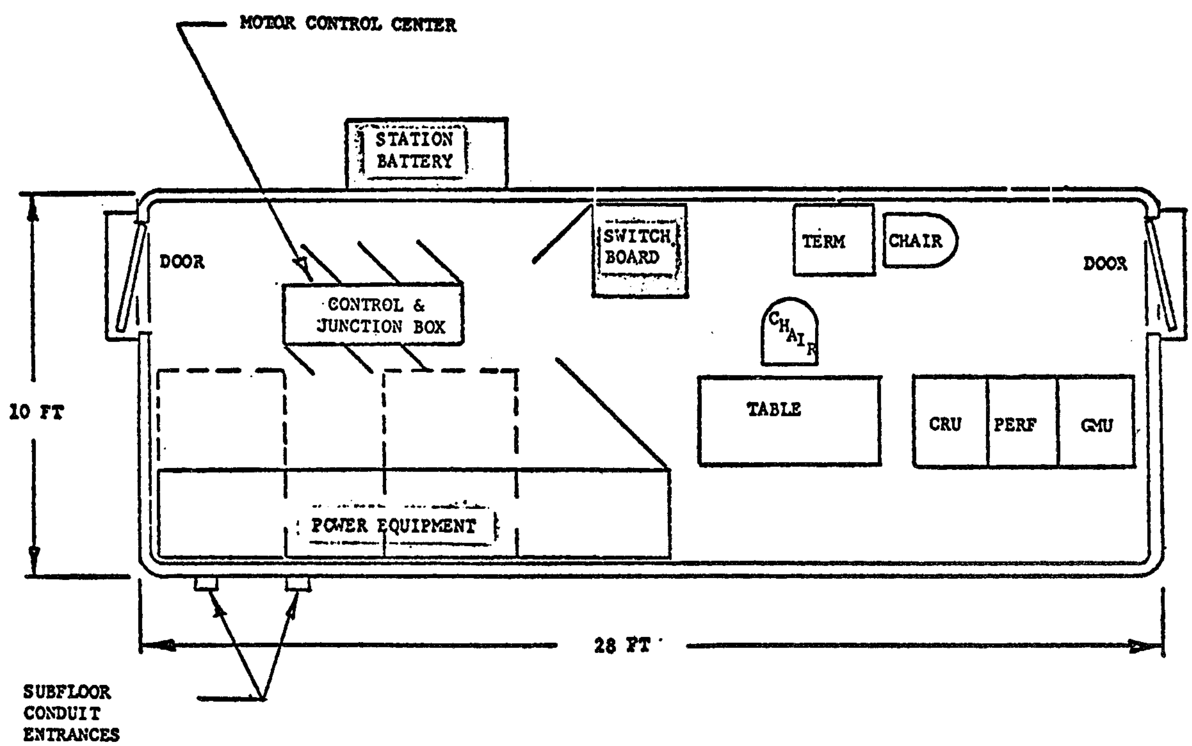

Figure 6-3. Enclosure Interior

SECTION 7

CONTROL AND INSTRUMENTATION SUBSYSTEM

SECTION 7 CONTROL AND INSTRUMENTATION SUBSYSTEM

7.1 FUNCTIONAL DESCRIPTION

7.1.1 CONTROL FUNCTIONS

The Control Subsystem has the following basic functions:

1. Control the rotor blade pitch angle to start up, supply subrated power at wind speeds between 11 and 24.6 mph, and rated power at wind speeds between 24.6 and 35 mph.

2. Control the yaw drive and brake hydraulic subsystem to drive the nacelle in yaw and apply the yaw and generator shaft brakes.

3. Provide for dispatcher control.

4. Condition and buffer sensor signals for internal use and the NASA Engineering Data Aquisition System.

5. Provide an operator interface.

6. Record data, commands and status for diagnostic purposes.

These functions are performed automatically and unattended during changes in internal system parameters as well as changes in wind speed and direction. A detailed set of functions with descriptions is listed in Table 7-1.

Table 7-1. Control System Functions

Function	Description
Monitor Enable	Process Lockout Sensors, Initialize Commands
Initialization	Initialize Yaw, Pitch, and Lube Subsystems
Site Enable	Process Automatic Restart Sensors
Anti-Stall	Limit β as a f(Vw) to Prevent "Stall"
Overstress	Limit Structural Stress as a f(W, Yaw Error)
Yaw Correct	Align Nacelle With Wind Vector
Pitch Ramp	Ramp β 90^{o} to 72^{o} - Maximum Coefficient of Lift
Speed Ramp	Ramp Generator Speed 0 to 1800 rpm
Rate Sync	Set Freq. Generator = Freq. Utility
Voltage Sync	Set Voltage Generator = Voltage Utility
Angle Sync	Enable Switch Gear Synchronizer, Wait for Breaker Close
Power Ramp	Step Power in 75 kW Increments 1 Sec. Apart
Shutdown	Disengage Utility, Feather Blades, Brake, Park Rotor
Power Peaking	Iterate Power Set - Point to Max. Value for $11 \leq VW \leq 24.6$

The pitch control function is designed to control pitch angle to regulate generator output to match the power reference. This is the main function which directly controls the power, but the other functions listed are required to make the machine practical.

Control system logic provides for protective shutdown. Table 7-2 describes the types of system shutdown and gives the criteria for each.

Table 7-2. WTG Shutdown Logic

Type of Shutdown	Description	
Normal	1. Yaw off if failure 2. Power down (pitch change) 3. Breaker open 4. Slow down (speed ramp) 5. 3-9 stop	Manual command Dispatcher command Wind speed drops below 11 User subsystem failure Wind speed - yaw error out of band Temperatures out of band Average wind speed above 35 Emergency pitch hydraulic pressure low
Emergency	1. Yaw off if failure 2. Pitch emergency feather 3. Breaker open 4. 3-9 stop	Frequency out of band Shaft speed too high Main breaker open Utility voltage dip below limit Wind speed - yaw error out of band Any vibration above limit Data link anomoly
Utility Outage	Emergency feather, yaw motor off, brake on, shaft brake off	Utility voltage drops out
Pitch Jam	1. Pitch emergency feather 2. Yaw 90° to wind and track	Blade will not respond

7.1.2 MANUAL FUNCTIONS

Manual functions required for debug, calibration and test operations are available on-site. These functions may be used by the on-site operator, one at a time, and will be continuously monitored by the computer to prevent any dangerous combinations.

7.1.3 BACKUP OVERSPEED SHUTDOWN

A separate circuit is used to bypass all software to feather the blades. Figure 7-1 is a functional block diagram of the design approach. If, for any reason (including any computer failure), the hub should reach 105% to 110% of rated speed (field adjustable), the "Backup Overspeed Shutdown" device will open a contact in series with the emergency feather solenoid coil. Since these redundant solenoids are arranged in a "deadman" configuration where coil current is required to keep them closed, the interruption of the power line redundantly initiates emergency feather action.

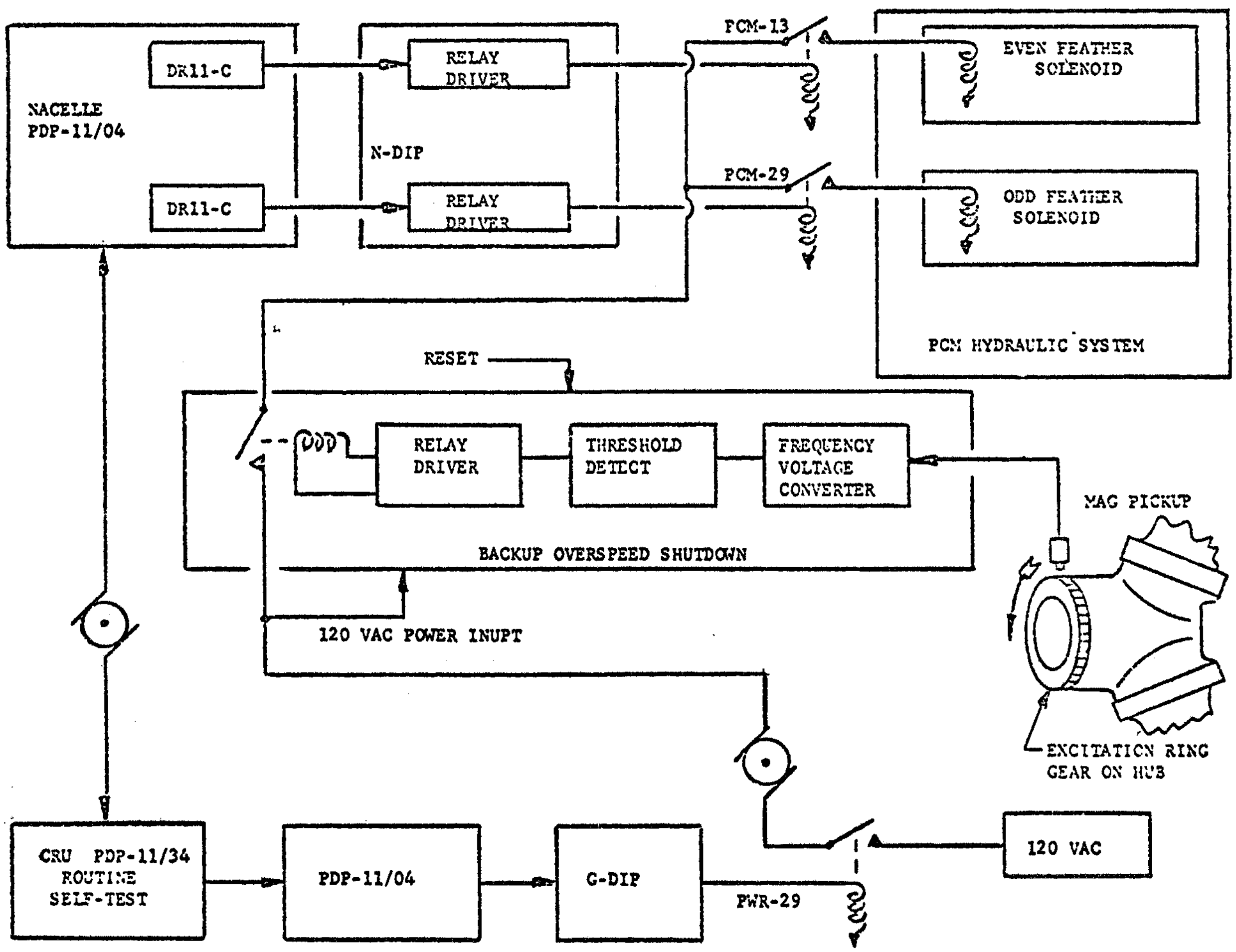

Figure 7-1 Emergency Shutdown Redundancy

7.1.4 SUPPORT FUNCTIONS

7.1.4.1 Reporting

An unsolicited on-site report will be automatically generated once an hour. Figure 7-3 is a representation of this report which will be printed out on the LA 36 DEC writer if its switch is on.

CUMULATIVE DATA	
1.75329E+04 HOURS	
GENERATED KW HRS	2.6298E+07
KVAR HRS	1.9285E+06
AUXILIARY KVA HRS	3.2123E+03
ELECTRICAL EFFICIENCY	0.2345 OVER TOTAL TIME
WIND MPH-HRS	3.8570E+05
AVERAGE KW/MPH	6.9876E+01
TOTAL BREAKER OPERATIONS	8.7650E+03
BREAKER OPERATIONS PER HOUR	4.9999E-01
OVERSPEEDS	51 ABOVE 105 PERCENT

Figure 7-3 Report Example

7.1.4.2 Recording

For development only, historical operational data will be recorded on magnetic tape. The tape will consist of all traffic between the Control and Recording Unit (CRU) and each of the Remote Multiplexer Units (RMU's), all traffic between the CRU and the Utility, all interface between the CRU and the on-site operator when the system is in the Automatic Mode, and all internal state changes. Recorded data will be available to interested personnel via playback processor when the WTG system is not operating.

A disk is allocated to record operational data, in wrap-around fashion, to allow diagnosis of shutdowns when the magnetic tapes are no longer used.

7.1.4.3 Dispatcher Communications

Dispatcher Communications are comprised of a subset of Operator Communications and consist of:

1. Sign On/Sign Off - identify self to system

2. Utility Enable - authorize the system to go to Generate

3. Power Set - query and alter the level of generation to which the system is currently attempting to adhere

4. Shutdown - direct the system to idle and stay there until Utility Enable is received

7.2 EQUIPMENT DESCRIPTION

7.2.1 MULTIPLEXER RACKS

There are two multiplexer racks in the Control Subsystem, one in the nacelle and the other in the Control Enclosure. These racks are essentially alike except the nacelle rack contains the Servo Controller, an air conditioner and heater, and is insulated with one-inch thick polyfoam. Therefore, the NMU Rack is described and a separate treatment of the GMU Rack is not given. Figure 7-4 is a photograph of the NMU Rack with a description of each of the GE designed components on the right and the purchased components on the left side. The following paragraphs describe each of the components in the NMU Rack.

7.2.1.1 Digital Interface Panel (DIP)

The Nacelle Digital Interface Panel (N-DIP) provides all the circuitry needed to interface 32 user subsystem's digital sensors, 32 command relays, and 32 status feedback channels with the remote multiplexers in addition to test logic that allows both manual and automatic computer driven testing. The Ground DIP is identical except that the N-DIP has 32 channels and the G-DIP has 16 channels.

7.2.1.2 Control Electronics (CE)

The Control Electronics component is used to interface the analog sensor signals with the analog-to-digital (A/D) converters in the multiplexers, receive commands for test mode selection, and buffer Servo Controller commands and remote Engineering data NASA Mux signals.

7.2.1.3 Remote Multiplexer Unit (NMU or GMU)

The remote Mux Unit consists of a PDP 11/04 computer built by Digital Equipment Corporation. The PDP 11/04 has 32K words of parity MOS memory, with the battery backup feature so that data stored in MOS memory will be retained when power is off. The computer also has a programmer console so that the computer may be operated without a computer terminal.

7.2.1.4 Servo Controller

The Servo Controller performs the analog control of blade pitch angle in response to mode and reference trim commands from the CRU and blade angle, hub speed, hydraulic valve spool position, and generator power from analog sensors as shown in Figure 7-7.

The Servo Controller regulates either generator shaft speed or power. A tachometer/precision reference combination provides an error signal when the generator speed does not match the reference. In power mode, the error signal is the difference between a CPU supplied reference and the output of a power transducer. The error signals are fed to an integrator and compensation circuits before they are amplified and converted to a current signal to drive the electro-hydraulic servo valve. The Nacelle Mux Unit transmits the analog speed and power trim signals which are used for rate sync and for limiting power to a value below rated capacity.

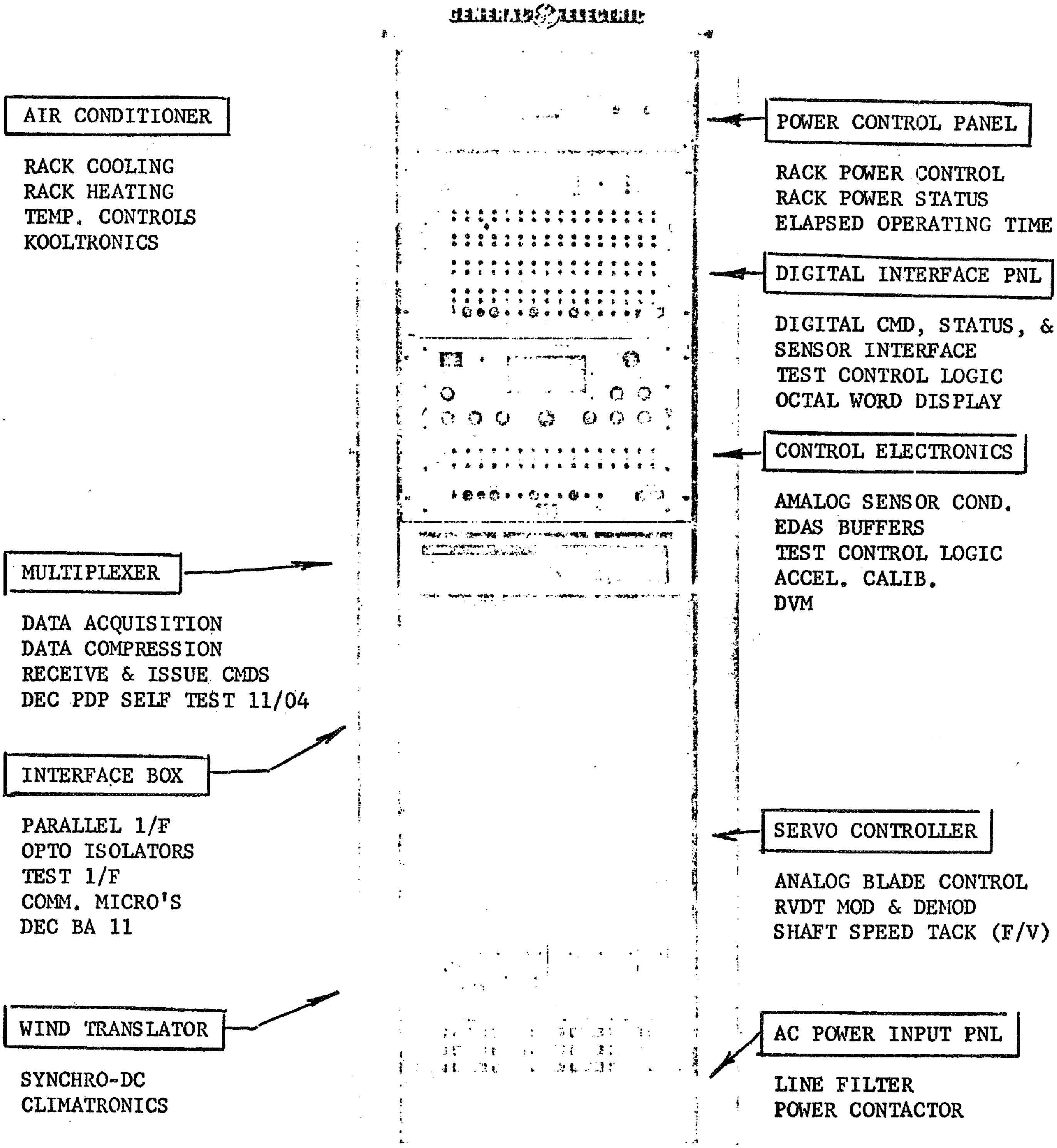

Figure 7- 4 Nacelle Mux Unit (NMU) Rack (Ice Box)

7.2.2 CONTROL AND RECORDING UNIT (CRU) AND PERIPHERAL RACKS

The CRU and Peripheral Racks, located in the Control Enclosure, contain the main process control computer, the mass storage disk drives, the real time clock for time tagging data, and the telephone line modem and auto caller. Also included in this section is the operator input/output device. Figure 7-8 is a photograph of the CRU and Peripheral Racks and lists a short description of each of the components.

7.2.2.1 Control and Recording Unit (CRU)

The Control and Recording Unit consists of a PDP 11/34 computer built by Digital Equipment Corporation. The PDP 11/34 has 64K words of parity MOS memory, with the battery backup feature so that the data stored in MOD memory will be retained when power is off. The PDP 11/34 also has memory management so that up to 128K words of memory may be used. In order to run the RSX-11M operating system, a programmable real time clock is provided. This unit provides interrupts up to 10 msec apart.

7.2.2.2 Disk Units

The CRU utilizes two RK05 disk units as the system program mass storage. Each disk stores 2.5 megabytes of data. The RSX 11M system and all system software, as well as the archive diagnostic data, is stored on the disk units.

7.2.2.3 Real Time Clock

The CRU uses a Datum 9100 real time clock, with 1 msec resolution to indicate when events occur. The time is read using a DR11C interface. The Datum clock also has a battery backup to insure that an accurate time record may be maintained despite power failure lasting 60 hours.

7.2.2.4 Auto Call and Modem

The CRU may contact a utility terminal or receive system status inquires via a VADIC 1601 Auto Calling Unit (ACU) and VADIC 301 Modem. The ACU is controlled by a DEC DN11-DA ACU interface. Serial communication is accomplished via a DL11-E serial interface at a data speed of 300 baud.

7.2.2.5 Operator Terminal

The device used for operator input and output is the DEC LA36 "DECwriter". This keyboard printer prints messages and reports from the CRU and gives commands typed in by the operator.

7.3 ENGINEERING DATA ACQUISITION SYSTEM (EDAS)

The Engineering Data Acquisition System (EDAS) provides data for structural, aerodynamic, and electrical performance evaluation of the WTG System. This system is described in detail in the NASA Statement of Work. Basically, the system hardware consists of three 32 channel Remote Multiplexer Units (RMU), a Stand-Alone Instrument Recorder (SAIR), and a Portable Instrument Vehicle (PIV).

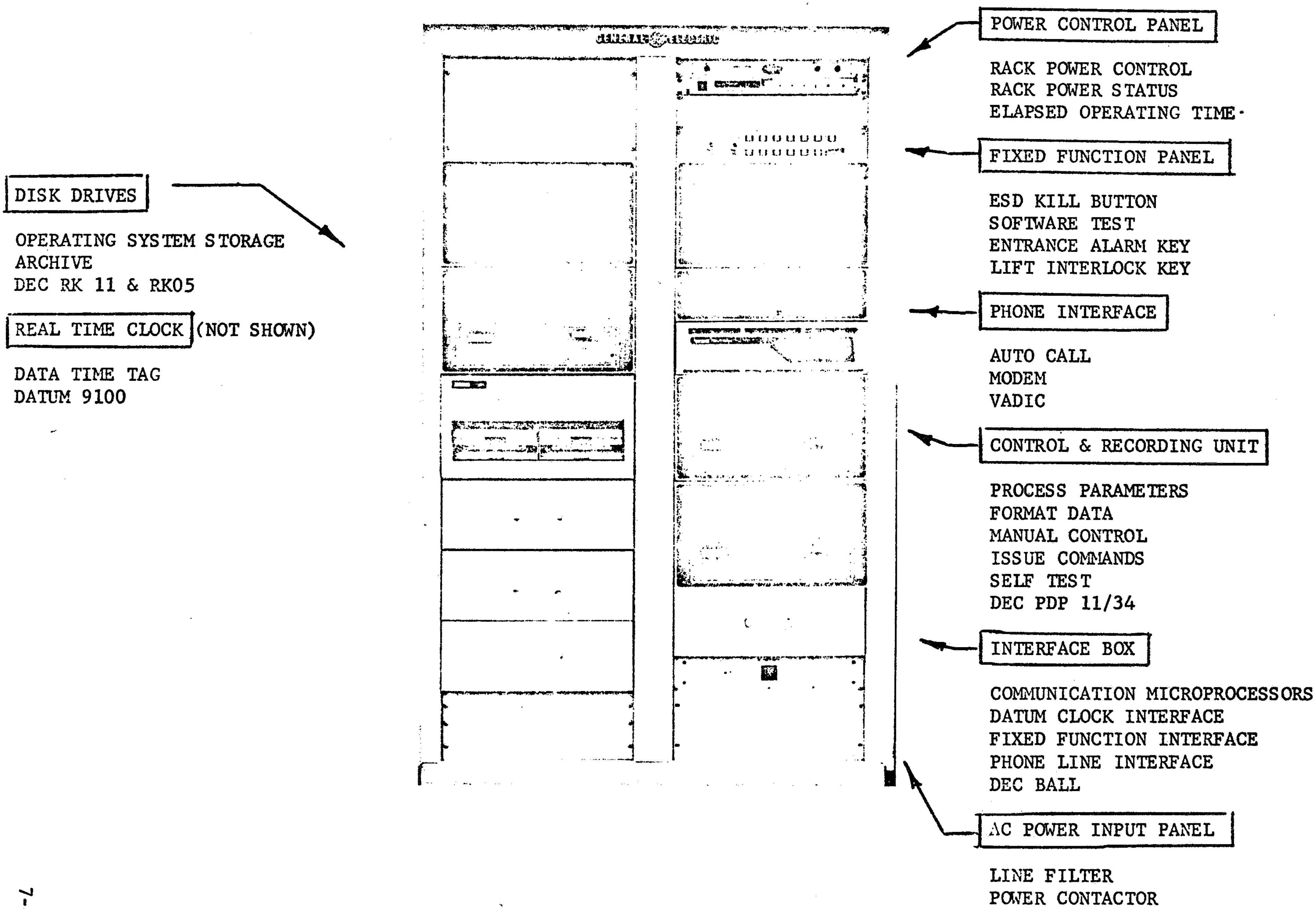

Figure 7- 8 CRU and Periferal Rack Configuration

7.4 SOFTWARE DESCRIPTION

7.4.1 FUNCTIONAL FLOW

The WTG software system is comprised of two parts, Process Control and Auxilliary Functions as shown in Figure 7-10.

The Process Control function is performed in three computers, the Control and Recording Unit (CRU), the Nacelle Multiplexer Unit (NMU) and the Ground Multiplexer Unit (GMU). The GMU and NMU are used for data collection and data concentration. They provide the system link to the commands and sensors in the WTG. The CRU performs the analysis of sensor change data, and causes commands to be dispatched by the NMU and GMU as circumstances require. The Process Control function is clock-driven as opposed to interrupt-driven. A request is dispatched by the CRU to the GMU and NMU every 100 millisecond, which directs these multiplexers to sample data, compress it and report predetermined changes to the CRU. Commands initiated by the CRU are output by the multiplexers. Command completion is monitored; retry, when necessary, is performed;

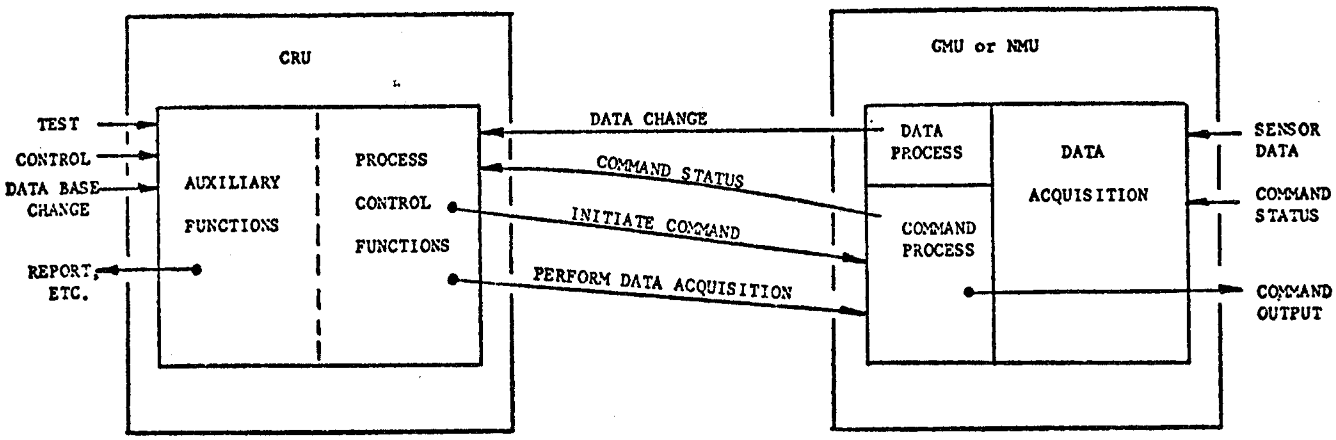

Figure 7-10. Software Overview Diagram

status, either pass or fail, is reported back to the CRU.

Auxiliary Functions (which consist of operator interface routines, utility interface routines, data base inspect and change routines, archive replay, report control, and manual system exercise) are handled primarily in the CRU. They are implemented as "background" tasks and executed during time remaining between end of Process Control function and the next tick of the 100 millisecond Process Control Clock.

7.4.2 SYSTEM FUNCTIONAL ALLOCATION

Three basic functions are performed by the WTG software system. They are: Process Control, Data Recording, and Auxiliary Functions. The Process Control Function is carried out in all three processors; the CRU, GMU and NMU. In the CRU, Process Control is performed by Data Acquisition, Control Task, State Enable and Data Process Modules. In the GMU and NMU, Process Control is performed by Data Acquisition, Data Process, Output, Command Acquisition, Command Process, and Controls Interface Driver. Data Recording is performed entirely in the CRU via the Archive processor. Auxiliary functions are likewise carried out primarily in the CRU. The modules involved in the CRU invlude Display, Manual (Functions), Test (Build), Modify, Playback, Startup, and Report. Test Execute module executes in each of the CRU's.

7.4.3 TEST MODULES

Software test modules are provided to generate test data and to distribute test data in the Remote Units for the Final Software Validation Test.

Test Build/Modify accepts engineering data values for the analog sensors and ones and zeroes for the discrete sensors and will form the State Time data blocks. This module converts all the analog engineering data into their equivalent 12-bit analog values and places the analog and discrete data onto the RX01 Floppy Disks for both the GMU and the NMU. Initial raw data will be input from the VT52. Later, this data can be modified on the Floppies through the VT52. Test Build/Modify will also list the test data contents of the Floppy for verification purposes. In order to run the Operational Scenario Test and Anomalous Shutdown Tests, Test Execute will be down-line loaded to each remote. TXQT will retrieve the State Time data blocks and temporarily store them in the PDP 11/04 MOS memory for sequential processing. Upon receipt of a Data Acquisition request from the CRU, both Remote Units distribute a State Time data block to the appropriate input parts of their respective analog and discrete interface units. Then, control is passed back to the operational acquisition module to scan, acquire, and process the data as usual. TXQT continues to process all the State Time data blocks through last State Time when it signals the CRT and printer that the test is over.

An operational test capability for the various hardware interfaces is provided by the Self-Test function. The sensor and command interfaces are periodically presented with known data values. They are then read and the input is compared to the output. Any detected anomolies between the two data sets result in an RMU initiated shutdown.

1. Report No. NASA CR-159497	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle EXECUTIVE SUMMARY MOD 1 WIND TURBINE GENERATOR ANALYSIS AND DESIGN REPORT		5. Report Date March 1979
		6. Performing Organization Code
7. Author(s)		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address General Electric Co. Space Division P. O. Box 8661 Philadelphia, PA 19101		11. Contract or Grant No. NAS 3-20058
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address U. S. Department of Energy Division of Distributed Solar-Technology Washington, D.C. 20545		14. Sponsoring Agency Code Report #DOE/NASA/0058-79/3

15. Supplementary Notes Final Report - Executive Summary
Prepared under Interagency Agreement EC-77-A-29-1010
Project Manager, R. Puthoff Wind Energy Project Office
NASA Lewis Research Center, Cleveland, Ohio 44135

16. Abstract

The Mod 1 program is being conducted in six phases: Analysis and Preliminary Design (culminating in a Preliminary Design Review), Detail Design (ending with a Final Design Review), Fabrication and Assembly, System Testing, Site Preparation, and Installation and Checkout. Major milestone dates for these phases are shown in Table 1-1. This report is intended to describe only the results of the first two phases; that is, activities leading to the completion of Detail Design. Although this report places emphasis on a description of the design as it finally evolved, it also traces the steps through which the design progressed in order to understand the major design decisions.

17. Key Words (Suggested by Author(s)) Wind Turbine Generator; MOD 1 WTG Final Report - Executive Summary	18. Distribution Statement Unclassified - unlimited STAR Category 44 DOE Category UC-60

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	60	

* For sale by the National Technical Information Service, Springfield, Virginia 22161

☆ U.S. GOVERNMENT PRINTING OFFICE: 1980 -657- 145/5217